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Sustainability in a Polymer Engineering Course: Evaluating the Student Experience

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Introduction

This full paper presents findings from an evidence-based practice study evaluating a sustainability intervention in a polymer engineering course. In some ways, the importance of sustainability has been recognized in engineering for decades. For example, in a 2004 report the National Academy of Engineering called for engineering education that prepares engineers for considering sustainability "in all aspects of design and manufacturing" [1, p. 21]. In 2006, the National Society of Professional Engineers added a professional obligation to its Code of Ethics encouraging engineers to follow principles of sustainable development [2], [3]. In his 2014 book, Dr. Trevelyan stated that the "ultimate challenge for today's young engineers is to find a way for all people to live in affordable comfort and safety within the limitations of this planet" [4, p. xxv]. This importance has only grown as engineers are tasked with addressing increasingly complex sociotechnical challenges such as biodiversity loss and climate change. Therefore, there is a pressing need for engineers and engineering students to learn and use sustainable practices.

However, engineering education has typically focused on economic-based decision making, at times balancing economic and environmental aspects, and even less frequently considering all aspects of sustainability and sustainable development: economy, environment, society, and future generations. In addition, recent study on engineer complex problem-solving approaches found that participants emphasized attention to technical dimensions over social dimensions when considering individual aspects and even more so when considering dimensions in relation to one another [5]. At Rose-Hulman Institute of Technology (RHIT) we noticed that sustainability has largely been incorporated into the curriculum through dedicated sustainability courses. Beyond these courses there is limited coverage of sustainability in our own departments. A more comprehensive review of sustainability curriculum at RHIT can be found in [6].

As educators, we felt tasked with bringing sustainability content into the classroom. We took the opportunity to learn how to incorporate sustainability into our current courses through participation in a RHIT-sponsored Sustainability Teaching Network (STN). This community of practice (CoP) created time and space for faculty across departments and programs to develop course updates and provided modest financial compensation for our development work. Ignited by this CoP, our course updates benefited from a transdisciplinary approach, as Dugan is in mechanical engineering and Chenette is in chemical engineering. This CoP also let us better align what we do in the classroom with industry expectations and with our institutions' new strategic plan, which has a theme around infusing sustainability into education [7].

We embarked on this study to understand students' learning, interest, and reception of the sustainability content that Chenette integrated into the course "Polymer Engineering" during Fall 2024. We sought to understand how chemical engineering students approached and reflected on a materials recommendation project: selecting a polymer for products made via injection molding. Our goal was to elicit details on how students ultimately arrived at their material recommendation and what they thought about the material selection process. By developing this work into an evidence-based practice paper, we also sought to provide an example of how sustainability content can be added to an existing course.

Background

Sustainability and Sustainable Development

Engineers are tasked with designing solutions to meet the needs of society, which often connect to the development of structures and products. The idea of *sustainable development* also gathers multiple interpretations, especially across different nations. Yet, most acknowledge "that it promotes prosperity and economic opportunity, greater social well-being and protection of the environment" which poses unique and complex challenges for the engineering community [8]. Both the Sustainable Development Goals (SDGs) put forth by the United Nations (UN) and the Engineering for One Planet (EOP) initiative provide frameworks with educational materials, including learning objectives and implementation guides [9], [10]. These frameworks focus on sustainable development, and sustainability, respectively.

Toward teaching and learning sustainability, Dr. Michel discusses the concept of sustainability in the context of higher education by naming and defining Education for Sustainability (EfS) and providing illustrative examples from literature [11]. EfS aims not only to promote awareness but to prompt deep learning, which Michel states "challenges students to ask philosophically deep questions" and "this deep questioning process has educational implications for increasing sustainable knowledge, attitudes, and behaviors" [12, p. 369]. Sustainability integration into curricula can happen in a variety of ways. Scholars encourage infusive modes of integration where content appears throughout the existing curriculum, rather than diffusive modes which involve dedicated new programs and courses [11].

There are a growing number of publications of sustainability integration into engineering education built around these sustainability frameworks and their resource guides. EOP examples can be found across chemical and biological [13], chemical [14], [15], civil and environmental [15], [16], and mechanical engineering [14] as well as materials science and engineering [15]. An example where SDGs are used is ongoing study of a multi-course integration in chemical engineering, where researchers use Sustainability-in-Action Elements along with SDG 12 "Responsible consumption and production" and the EOP principle of "Systems Thinking" to frame their exploration of how students learn and apply sustainability values [17].

Material Selection as a Tool for Sustainable Design

Several DfS approaches going back to the 1990s incorporate material selection [18]. From the oldest approach, *green design*, where material selection was one of the main interventions, to considering material impacts across a lifecycle in *product eco-design*, to selecting materials that support closed-loop material flows in *cradle-to-cradle* and *biomimicry* approaches. Given that sustainability challenges necessitate the use of a combination of DfS approaches [18], material selection continues to be a useful tool. For example, VentureWell has many tools for design and sustainability including those that support the selection of "greener materials" [19].

Material Selection Assignments in Engineering Courses

For over 20 years, researchers have published about their efforts to incorporate sustainability considerations into engineering education through material selection. While an exhaustive review of these efforts is outside the scope of this paper, many occurred within materials science or materials science and engineering departments. These efforts range from modifying a routine method, to a single class period module, to an integral aspect of a six to seven-week long project-based learning design project. For example, Kampe presented a case study around material replacement of asbestos insulation from a senior level “Materials Selection and Design” course [20]. This case study illustrated assessing a material’s environmental impact by calculating the material’s energy content value. Gelles and Lord developed a module for a third-year Materials Science course where material selection for a straw was used to engage students in considering social aspects of sustainability, specifically who benefits and who pays for a given material [21]. Finally, Ruzycki explored material selection and screening, along with Life Cycle Analysis (LCA) in a sophomore laboratory course of a materials science department [22]. In the design project for this laboratory course students determined the material composition of a given product, conducted an LCA to assess the product’s eco and social footprint, and were encouraged to focus on materials solutions to a problem statement they developed.

However, many of these publications have not explored students’ processes for selecting material(s), students’ descriptions of their experience, and how the experience will shape future action simultaneously. For example, Kampe’s paper focused on describing a method for calculating the environmental load of a specific material [20]. Ruzycki’s study explored how much students learned of various course topics and what key aspects of the course the students were still using in their current coursework a year later, based on a survey [22]. Findings were summarized in bar chart and word cloud form, respectively. Surveyed and reported topics included life cycle assessment, material selection, and material databases (e.g., CES EduPack). Ruzycki did share one student quote for the final survey question that focused on why students think they should be asked (if they even should) to learn about sustainable engineering practices. Finally, while Gelles and Lord’s paper did explore students’ processes for selecting material(s) their study focused on social aspects of sustainability and did not explore student reflections [21]. Thus, there are opportunities for explicit exploration of students’ processes when considering multiple aspects of sustainability and student reflections on these processes.

Course Overview

In an analysis by members of our institution, Polymer Engineering was classified as a D-Tier course—meaning it is a course with the potential for “many students [to] encounter” or “use[s] data from real examples from implements of sustainability” [6]. This elective course is offered yearly, comprised of 10 weeks of lecture-based instruction with approximately weekly individual assignments and reading quizzes, two mid-terms, a group project, and final exam. Historically this course contains four main units, with no explicit sustainability content (refer to Table 1).

Interventions developed with support from the STN comprised of scaffolding (two reading assignments in CEP magazine [23], [24], online webinar assignment [25], one-day Intro to LCA with EcoAudit tutorial [26]) and a materials recommendation group project (Appendix A) to replace the previous reverse-engineering group project. We considered incorporation of learning objectives associated with SDG 12 “Responsible consumption and production” and learning outcomes tied to EOP principles Environmental Impact Assessment (EIA) and Materials Selection (MS) for the group project, finding a subset of the EOP principles best aligned with the project scope. The authors developed a four-item rubric (Appendix B) to evaluate group projects based on specific learning objectives outlined in the EOP framework relating to EIA and MS and provided this to students with the project prompt.

Table 1: Polymer engineering course details

Title: Polymer Engineering (CHE 441) **Credit Hours:** 4 **Prerequisites:** Reaction Engineering (CHE 404), Organic Chemistry I (CHEM 251) **Required Textbook:** Fundamental Principles of Polymeric Materials (Brazel and Rosen, 2012)	**Catalog Description:** Interrelation of polymer structure, properties and processing. Polymerization kinetics. Methods for molecular weight determination. Fabrication and processing of thermoplastic and thermosetting materials. Student projects. **Course Units:** Polymer Principles: Synthesis and Kinetics, Polymer Properties and Characterization, Polymer Processing and Rheology, Advanced Topics and Project

Research Methods

Research Questions

This study represents a first step towards improving students' experiences with sustainability in a polymer engineering course. We sought to answer the following research questions:

RQ1) How do students in a polymer engineering class approach an assignment that explicitly requires considerations of sustainability?

RQ2) How do students perceive and report the effects of having to explicitly consider sustainability?

Participants

All 18 fourth-year chemical engineering students in Chenette's polymer engineering course consented to participate in this study and signed the informed consent document. RHIT's Director of Assessment assisted in ensuring IRB best practices, including handling consent forms and assisting with anonymizing all student documents.

Data Collection

Collected artifacts available for consideration in this study included documents that were required for the course. These include: a one-page summary and project report (part of project deliverables for group), the rubric score-sheet documenting the instructors' assessment of the projects, and an individual student reflection (part of project deliverables for each student). The reflection questions (Appendix C) were adapted from reflection models [27] and prompted participants to describe their project experience, if/why the experience was significant, and next steps. The instructor had access to original documents for the purpose of assigning course grades, however anonymized versions of these artifacts were reviewed for the purpose of this study.

Data Analysis

Our data analysis process was guided by Braun and Clarke's guide to reflexive thematic analysis (TA) [28], Saldaña's coding manual [29], and Walther et al.'s [30] recommendations for supporting the quality of qualitative research. The process of reflexive TA involves six phases starting with dataset familiarization, then data coding, followed by the generation of initial themes, theme development, and then theme refinement, and ending with writing up the analytic story [28]. We align our work with aspiring towards a qualitative paradigm. Thus, we do not report exact counts for theme frequency. The theory of language we draw on in our analyses is that language is intentional—it is conveying our participants perspective [28]. Furthermore, our analysis is grounded in critical realism where we understand the truth to exist but acknowledge that it is impossible for us to access the truth directly [28]. Therefore, we are not interested in the accuracy of participants analyses but rather what information they gathered, how they used the information they had, and what they learned from the experience.

We started data analysis with a focus on RQ2. We each read all participant responses to the first reflection prompt, followed by all responses to the second reflection prompt and then the third. As the course instructor Chenette had read all the reflections prior to analysis, so while reading the reflection responses she made brief analytic notes about her insights and organized these notes into five main codes. Dugan followed up data review with the first cycle coding method of process coding—using gerunds to mark actions—because this method aligned with questions that explore participant actions and perceptions [29]. Dugan then completed a second cycle of coding using pattern coding to pull first cycle codes into more meaningful groupings [29]. We then met to share our respective approaches and then individually tried to find parallels between our groupings and refine themes. We met again to enhance our understanding and interpretation of the data and decided to pursue further development of seven major themes. To support process reliability [30], Dugan used outcomes of author discussions to produce a document that distinguished between latent and manifest themes as well as the codes that supported each theme. To support communicative validation [30], we split up re-coding all the reflections followed by participant-by-participant review of each other's coding to clarify and strengthen our communication of findings to readers. Throughout this process, Chenette would acknowledge when coding sometimes took into account her experiences with students in the course and then would intentionally work to focus only on the information in the written reflections, supporting procedural validation by keeping data analysis focused on the artifacts she could review [30].

We started data analysis for RQ1 while continuing analysis for RQ2. Dugan reviewed four teams' summaries and reports making notes about what was interesting to them during the first read. After meeting with Dugan to debrief their initial process, Chenette reread the other four teams' summaries and reports and started to develop codes. After Dugan used these codes on two teams, we realized that we had many codes that were not directly addressing our research question so Dugan pivoted to analytic memos [29] focused on reflecting and writing tentative answers to RQ1. Our final analysis focused on how teams defend and qualify their final material recommendation. While many teams had similar approaches, we also highlight cases where a team differed to support theoretical validation [30].

Limitations

We cannot attribute everything in the reflection to students' experience with the materials recommendation project because sometimes students commented on other parts of the course or did not describe an explicit connection to the project. Our participants were tasked with putting forth a diligent and honest effort on the reflection which may have compelled some students to amplify their experience. Additionally, there were differing course resources that may have guided students' attention to economic and environmental impacts as opposed to societal impacts across the project summaries and reports. The project prompt required groups to articulate the broader impacts of a material based on at least one of the following: the product's embodied energy, CO2 footprint, or toxicity. While the Level 3 Polymer EcoAudit tool within Ansys Granta EduPack demoed in class provides price, embodied energy, and CO2 footprint, toxicity evaluation was not demoed in class. Finally, no definition of sustainability was formally introduced in the course. Therefore, our participants may have approached this project with a variety of ideas about sustainability and what is most important for their recommendation.

Findings

RQ1: How do students in a polymer engineering class approach an assignment that explicitly requires considerations of sustainability?

Direct assessment of approaches focused on four learning outcomes from the EOP framework [9] documented in Table 2. On average groups met the EIAC.1, EIAC.3, and MSC.4 learning outcomes, but several groups only partially met MSC.1 and one group failed to meet MSC.1.

Table 2: Materials recommendation project rubric categories map to EOP learning outcomes where 0 – Fails to Meet; 1- Partially Meets; 2 – Meets; 3 - Exceeds

Group	Environmental Impact Assessment Core 1 (EIAC.1)	Environmental Impact Assessment Core 3 (EIAC.3)	Materials Selection Core 1 (MSC.1)	Materials Selection Core 4 (MSC.4)
	Explain high-level environmental impact assessments (e.g., basic Life-Cycle Assessments (LCAs) and life-cycle hazards; i.e., how they work, what information they require, how to incorporate their findings into their work)	Interpret broader energy, climate, water, wastewater, air pollution, and land-use implications of their work by conducting basic environmental impact assessments (e.g., Life-Cycle Assessments, carbon footprints, toxicity)	Identify potential impacts of materials (e.g., embodied energy, emissions, toxicity, etc.) through the supply chain — from raw material extraction (accounting for reuse/recycling), through manufacturing, transport, use, and disposal — with justification for material selection focusing on a minimizing negative impacts to the planet and all people (i.e., especially those who have been intentionally marginalized)	Compare materials properties (e.g., chemical, physical, and structural properties) and performance aligned with end-use application
Blue	1	3	2	2.5
Yellow	3	3	3	2
Orange	2.5	1	1	2
Violet	2.5	2	1	3
Indigo	1.5	3	2	2
Green	2	3	2	1.5
Red	1.5	2	2	2
Black	2	1.5	0	3

Most groups only analyzed two materials—the project required a minimum of one traditional material and one novel material—but the Orange and Violet groups analyzed two novel materials. A novel material was defined as “one that that is non-traditionally used for such devices, and/or has potential for reduced global, social, economic, and/or environmental impact.” Table 3 summarizes the material each group analyzed and their material recommendation.

All groups gathered information on environmental and economic impacts across the product’s lifecycle as well as material properties. Most groups qualified their recommendation by indicating one or more situation in which their recommendation could change. For example, recommendations could change if certain material properties such as durability were more or less important (Yellow, Red, Black), if a material became more economically viable (Indigo), if the cost of the material was negligible (Black), if a material could be manufactured locally (Green), if there was a clearer "product needs to be more a sustainable option than [recommendation]" (Red), or if research on the material was further developed (Orange).

Table 3: Summary of the materials groups analyzed and groups' material recommendations

Group	Participants	Group Classified Traditional Material(s)	Group Classified Novel Material(s)	Recommendation
Blue	Blue 1 Blue 2	Polycarbonate (PC)	Polylactide (PLA)	Novel (PLA)
Yellow	Yellow 1 Yellow 2 Yellow 3	Blend of acrylonitrile butadiene styrene and polyvinyl chloride (ABS+PVC)	Styrene-Ethylene-Butylene-Styrene (SEBS)	Novel (SEBS)
Orange	Orange 1 Orange 2	Acrylonitrile butadiene styrene (ABS)	Polypropylene (PP); Polydiketoenamine (PDK)	Novel (PP)
Violet	Violet 1 Violet 2	Acrylonitrile butadiene styrene (ABS)	Thermoplastic polyurethane (TPU); Polycaprolactone (PCL)	Novel (TPU)
Indigo	Indigo 1 Indigo 2	Acrylonitrile butadiene styrene (ABS)	Polyhydroxyalkanoates (PHA)	Traditional (ABS)
Green	Green 1 Green 2	Acrylonitrile butadiene styrene (ABS)	Linear low-density polyethylene/Natural rubber (LLPE/NR)	Traditional (ABS)
Red	Red 1 Red 2	High-density polyethylene (HDPE)	Polylactide (PLA)	Traditional (HDPE)
Black	Black 1 Black 2 Black 3	High-density polyethylene (HDPE)	Thermoplastic starch (TPS)	Traditional (HDPE)

Material properties were frequently a deciding factor for groups' recommendations and/or a reason for which their recommendation could change. All groups used cost as a deciding factor for their recommendation. All groups that recommended the traditional material either had cost as their sole deciding factor or cost and one other factor. On the other hand, all groups that recommended a novel material had a more holistic justification for their decision covering material properties, economic and environmental impacts. While most groups gathered information on toxicity, no groups used toxicity in their justification of their recommendation.

RQ2: How do students perceive and report the effects of having to explicitly consider sustainability?

We identified seven themes on how our participants perceived and reported the effects of having to evaluate possible polymer materials for injection molded products.

Theme 1: Several participants responses indicate considering sustainability means dealing with ambiguity. This was expressed in a variety of ways from participants sharing that the project was open-ended, overwhelming, or vague.

Theme 2: All participants noted that considering sustainability requires learning new knowledge or skills. This was evident in how participants mentioned having some priority knowledge or familiarity with sustainability-related content following by descriptions of either a lack of experience with sustainability-related content or things they learned. This theme was also supported by how several participants made claims about information they would now be able to share with future co-workers such as how material selection impacts sustainability, sustainability metrics, and alternate polymers.

Theme 3: Many participants disclosed ways in which considering sustainability is a complex or challenging task. For example, participants discussed the presence of numerous factors, identified tradeoffs broadly or described specific tradeoffs, and shared that it is hard to quantify certain effects, find certain polymer properties, or compare impacts across different scales. In addition, some participants wrote about the need to be open to results you would not expect.

Theme 4: Most participants responses indicated considering sustainability involves considering circular processes. For example, participants commented on learning about end-of-life consequences, nuances of biodegradability, recycling, the importance of considering the entire lifecycle, Eco Audits, chemical circularity, and circular economies or wrote about the need for polymers that can be recycled or biodegraded.

Violet 2's description of their experience with the project supports Themes 1, 2, 3 and 4.

> *My initial expectation was that there would be an obvious "better option" in terms of materials. When doing research and using the Granta EduPack tool, I realized there were a lot more trade-offs than I first thought. I have not taken a sustainability class, so by doing research for this project, I was able to understand that it consists of the entire life cycle of a product. If we only focus on the raw material extraction and manufacturing, we are forgetting the end-of-life consequences which may have an even greater impact.*

Theme 5: An effect of having to consider sustainability is developing new interests or returning to old ones. Most participants brought up new or renewed interests. Participants shared new or renewed interests ranging from sustainability broadly to those focused on materials or those focused on real-world practice. Interests related to materials included wanting to learn more about adapting current practices or materials, to develop or evaluate new materials, to learn more about how polymer biodegrade. Interests related to real-world practice included making connections to career interests, wanting to know more about company incentives to produce environmentally friendly products, and how or why professionals make material selection decisions.

Theme 6: Responses from half of our participants demonstrated that considering sustainability illuminates for participants that chemical engineers are limited by existing structures. Participants mentioned several barriers to introducing (more) environmentally friendly materials such as a lack of infrastructure or tradeoffs, for example between the environment and economics. Participants described companies' specific priorities as either a barrier or a strong influence in terms of what decisions chemical engineers can make.

Theme 7: Responses from half of our participants demonstrated that considering sustainability gave participants insight into the ways chemical engineers can affect change. Chemical engineers can consider a product's end-of-life, consider impacts across a product's lifecycle, reduce process energy use, implement circular processes, change mindsets around sustainability, and invest in the research and development of sustainable materials and processes.

Orange 1’s description of next steps supports Themes 5, 6, and 7.

> *I believe the next step for me specifically is to just continue to educate myself on sustainability topics. If I continue to educate myself, I can help educate others, and the more educated that everyone is on topics related to sustainability, the easier it will be to make progress on sustainability efforts… Working for [oil company] definitely conflicts with my interest in sustainability, due to petroleum refining being a process that is not exactly environmentally friendly. However, [oil company] has an environmental department and is beginning operations of a renewables facility, and that may be something that I am able to pursue in the future. Chemical engineers can consider sustainability into their work by continuing to process optimize and possibly incorporate renewables where possible. We can design and operate processes that minimize energy use, such as using heat integration techniques where waste heat from one part of the process is reused in another.*

Discussion

In summary, our participants usually met the EOP learning objectives around explaining high-level EIAs, conducting basic EIAs, and comparing material properties, but struggled the most with justifying material selection in a way that attended to both the planet and people. We suspect the relative difficulty in accessing toxicity information, in comparison to information on a material’s price, embodied energy, and CO2 footprint likely contributed to this result.

Several of our findings aligned with SDG 12 “Responsible consumption and production” learning objectives [31]. The fifth cognitive learning objective is “The learner understands dilemmas/trade-offs related to and system changes necessary for achieving sustainable consumption and production.” Most groups approached this materials recommendation project by qualifying their recommendations demonstrating their understanding of the impact different priorities can have. In addition, many of our participants reflected on the ways that considering sustainability is complex or challenging (Theme 3) and this often showed up as calling out tradeoffs broadly or describing specific tradeoffs. Furthermore, half of participants recognized ways that chemical engineers’ consideration of sustainability is limited by current structures (Theme 6) illustrating their understanding of dilemmas and barriers to change. The second socio-emotional learning objective is “The learner is able to encourage others to engage in sustainable practices in consumption and production.” Several participants made claims about information they would now be able to share with future co-workers such as how material selection impacts sustainability, sustainability metrics, and alternate polymers (Theme 2). Finally, the third behavioral learning objective is “The learner is able to promote sustainable production patterns” and half of our participants wrote about ways chemical engineers can affect change (Theme 7).

Other themes also align with core concepts in sustainability. For example, most participant responses touched on circular processes in some way ranging from end-of-life consequences to circular economies (Theme 4). The principles of reduction of resources, reuse, and recycling are at the center of the concept of a circular economy and connect the concept of a circular economy to several DfS approaches such as *cradle-to-cradle* and *biomimicry* [18]. In addition, several participants touched on the ambiguous nature of grappling with sustainability (Theme 1). This ambiguity combined with the complexity and challenging nature of considering sustainability

(Theme 3) makes sense as sustainability is one of the cross-cutting themes for the Grand Challenges for Engineering in the 21st century [32].

Based on most groups meeting the several EOP learning objectives and the alignment of several reflection themes with SDG 12 learning objectives and sustainability concepts, we find that this initial integration of sustainability content in the course to be promising. It is important to note that the success we have observed is supported by best practices associated with the 'Teaching for sustainability' arm of Michel's proposed framework for Teaching and Learning for Sustainability in Higher Education [33]. The project centered on a transdisciplinary approach with the deliverable intended for students in a subsequent mechanical engineering course, representative of the "connecting to the here and now" practice. By promoting student ownership of the materials recommendation, the project "empower[ed] the learner." Facilitating reflection as part of the project aligns with "contemplative practices" and the use of in-class discussions to debrief various webinar viewings exemplifies "active learning pedagogies".

Implications

We have illustrated how sustainability frameworks, specifically EOP and the SDGs [9], [10], provided scaffolding for Chenette to infuse sustainability content into her polymer engineering course. With Chenette making relatively few changes, our analysis suggests these changes were sufficient for students to have meaningful experiences engaging with sustainability. We believe Chenette's intentional use of sustainability frameworks helped create these meaningful experiences and recommend educators seeking to integrate sustainability into a course to use at least one sustainability framework for guidance. In the next iteration of the course Chenette will run the project again and will provide more resources for considering societal impacts, e.g., toxicity. She will also formally introduce the definition of sustainability from the EOP framework [9] to help emphasize to students the importance of attending to social systems in addition to environmental system while further anchoring the class in best practices in EfS such as co-constructing a definition of sustainability in class [33].

Conclusion

In this evidence-based practice study, we described adding sustainability content to an existing course and examined chemical engineering students' approaches to a materials recommendation project and their reflections on the impact of having to consider sustainability. Our analysis of students' approaches focused on how teams defend and qualify their final material recommendation, while our thematic analysis of students' reflections focused on capturing salient effects of the experience. While student groups varied in which factors and how many factors informed their material recommendation, economic aspects of sustainability (e.g., cost to produce and manufacture the material) were the most pervasive factors. We suggest more resources related to other aspects of sustainability could support students in conducting more holistic analyses in future offerings of Chenette's polymer engineering course. In addition, we identified seven themes on how participants perceived and reported the effects of considering sustainability. These themes connected to the ambiguity, complexity, and circular nature of sustainability while also touching on ways considering sustainability prompts new learning, new or renewed interest, and recognition of both the limitations of possibilities for chemical engineers to affect change.

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Appendix A: Project Prompt

CHE441: Polymer Engineering | Fall 2024

Materials Recommendation Project

You are a chemical engineer for a large manufacturing company. The manufacturing team (ME317 students) has been tasked with designing products made via injection molding and requests you to evaluate possible polymer materials and make a recommendation to their team. The products themselves are not yet specified, but they will be some type of hand-held enclosure (e.g., tape measurer case, restaurant pager device), which is considered the end-use application. Desired material properties should be appropriate for such product. Your task is to use your expertise in polymer engineering to evaluate at least two material solutions, including at least one traditional (e.g., ABS, ABS/PC, PC, HDPE, etc.), and at least one “novel” material to address sustainable consumption and production challenges. In addition to evaluating material properties (e.g., chemical, physical, and structural properties) through a technical lens, your evaluation should critically analyze these material solutions’ potential global, social, economic, and environmental impacts. The scope for this analysis is cradle-to-grave.

In this case, “novel” is quite broad, but a novel material is one that that is non-traditionally used for such devices, and/or has potential for reduced global, social, economic, and/or environmental impact (some novel examples might be PIM - biobased material of pulp, starch, and water; Nissei Plastic Industrial Co.’s plastic wood composite material; PLA; etc.).

<u>Deliverables:</u>
Group Deliverables (one per group):

- **Recommendation Summary** (1 page, audience: manufacturing team): for each material solution (must evaluate at least 2) concisely articulate the expected material performance, processing constraints, and broader impacts of the solutions based on at least one of the following: the product’s embodied energy, the product's CO_2 footprint, the product’s toxicity. Must state and justify the material recommendation.
- **Full Report** (5 pages not including figures and references, audience: manufacturing team manager with an engineering background):
    1. Project Introduction: context and approach
    2. Background: information on environmental impact assessments, literature review of materials
    3. Results (including assumptions, calculations)
    4. Interpretation of Results
    5. Conclusions
- **Group Presentation** (15min): Mimic full report structure but should focus on results and interpretation.

Individual Deliverables (one per individual):

- **Written reflection** on the project (separate prompt)

<u>Due date:</u>
Recommendation Summary – due Monday of Finals Week
Full Report – due Monday of Finals Week
Group Presentation – Th and Fr of 10^{th} week
Written Reflection – due Tuesday of Finals Week

<u>Assessment:</u>
See rubric.

Appendix B: Project Rubric

Group Info:

	EOP Learning Outcomes / Evaluation of Expectations	0 - Fails to Meet	1 - Partially Meets	2 - Meets	3 - Exceeds
EIA.C.1	Explain high-level environmental impact assessments (e.g., basic Life-Cycle Assessments (LCAs) and life-cycle hazards; i.e., how they work, what information they require, how to incorporate their findings into their work)	fails to articulate basic purpose and requirements (two or more major omissions or inaccuracies), and/or fails to incorporate findings (lacks context and/or implications)	articulates basics of purpose and requirements (two minor or one major innacuracy or omission) , demonstrates an attempt to incorporate findings into deliverable but context or implications are lacking or misaligned	articulates basics of purpose and requirements sufficiently (minor omission or inaccuracy), demonstrates appropriate incorporation of findings but context is general and/or implications are overly broad	articulates basics of purpose and requirements accurately and completely, demonstrates appropriate incorporation of findings into deliverable providing relevant context and thoughtful implications
EIA.C.3	Interpret broader energy, climate, water, wastewater, air pollution, and land-use implications of their work by conducting basic environmental impact assessments (e.g., Life-Cycle Assessments, carbon footprints, toxicity)	incomplete or overly-simlified impact assessment leading to interpretations that are either inaccurate, trivial, or lacking meaning	appropriately detailed impact assessment (e.g., carbon footprint and/or energy) with an attempt to interpret broader implications in appropriate impact areas (e.g., energy, water, air pollution)	appropriately detailed impact assessment (e.g., carbon footprint and/or energy) with interpretation aligned with broader implications in appropriate impact areas (e.g., energy, water, air pollution)	appropriately detailed impact assessment (carbon footprint and/or energy) that also includes toxicity with interpretations aligned with outcomes from assessments in appropriate impact areas
MS.C.1	Identify potential impacts of materials (e.g., embodied energy, emissions, toxicity, etc.) through the supply chain — from raw material extraction (accounting for reuse/recycling), through manufacturing, transport, use, and disposal — with justification for material selection focusing on a minimizing negative impacts to the planet and all people (i.e., especially those who have been intentionally marginalized)	identifies at least one potential impact for zero or one of the 5 stages of the supply chain, in each case articulates (with evidence) the degree to which their selection may minimize negative impacts to the planet and people	identifies at least one potential impact for two or three of the 5 stages of the supply chain, in each case articulates (with evidence) the degree to which their selection may minimize negative impacts to the planet and people	identifies at least one potential impact for four or five of the 5 stages of the supply chain, in each case articulates (with evidence) the degree to which their selection may minimize negative impacts to the planet and people	identifies at least one potential impact for four or five of the 5 stages of the supply chain, in each case articulates (with evidence) the degree to which their selection may minimize negative impacts to the planet and people, and discusses how improvements/changes to the 5 stages could further minimize negative impacts
MS.C.4	Compare materials properties (e.g., chemical, physical, and structural properties) and performance aligned with end-use application	fails to compare sufficient number of materials (or material properties) and/or fails to evaluate performance of end-use requirements	compares less than sufficient number of materials (or material properties) and attempts to evaluate performance related to end-use requirements but contains omissions or inaccuracies	compares sufficient number of materials (and material properties) and evaluates performance related to end-use requirements (may contain minor omission or inaccuracy)	compares more than the sufficient number of materials (and material properties) and evaluates performance related to end-use requirements

Comments:

Rubric adapted from Engineering for One Planet Learning Outcomes

Appendix C: Reflection Questions

CHE441: Polymer Engineering Fall 2024

Written Reflection Prompt

This reflection includes three sections. Each section has several guiding questions*. You do not have to answer each question listed under each section. Instead, consider answering those questions that resonate with you. In your responses, please consider the Materials Recommendation Project, and any related aspects of the course (CHE441 Polymer Engineering). There are no right or wrong responses. Giving a diligent and honest effort in your response to each section will result in full credit for this reflection assignment.

*Questions are adapted from "Reflection Models" Center for Excellence in Teaching and Learning: Educational Technologies, University of Connecticut, 2024, https://edtech.uconn.edu/portfolios/reflection-models/

1. **1. Describe your experience with the project.** What issue was the project addressing? What were your initial expectations for the project? What did you already know about sustainability as you explored the project? What did you learn from completing the project?

2. **2. Describe why this experience was significant (if it was).** What new skill did you learn? What critical questions did this project cause you to ask? What about the project stuck out to you/made an impact on you? What values, opinions, decisions have been made or changed through this experience? What are some of the pressing needs/issues related to this project? How has your understanding of sustainability changed as a result of your participation in this project?

3. **3. Describe next steps.** What would you like to learn more about, related to sustainable materials? What information about sustainability can you share with your co-workers, manager, or peers at your first job? Have your career interests changed or shifted by your participation in this project? How can chemical engineers better consider sustainability in their work?