Design for the future: Analyzing the broader implications of electronic technologies in an introductory engineering class

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***Abstract*— This innovative practice full paper shows how considerations of social, environmental, and economic context were integrated into a required introductory course on electrical engineering. We describe the content, implementation, and results of a "Design for the Future" module conducted in Spring 2019. This module is framed around a course-long student project where students choose a technology of interest (TOI) to them that relates to electrical engineering, (e.g. Tesla batteries, solar cells, and tidal-powered turbines). The module includes a student proposal; lectures and discussions interrogating how to determine and define sustainable technologies and how these can be improved; a memo homework asking students to consider the design of a solar farm; an in-class worksheet exercise designed to help students consider the design implications of who benefits, who pays, and who is excluded in relation to their TOI; and, finally, students present and submit a report on their TOI. Student feedback in surveys and a focus group showed that the module enabled students to think more deeply about the broader implications of technologies and their electrical components. We provide a reflection on the successes and areas for improvement of this module, along with module materials, with the hope that they might help others incorporate them into their courses towards developing the capacity among engineering students to address broad considerations that support values such as sustainability and social justice.**

Keywords—implications of design, social, environmental, and economic context, electrical engineering, design for the future

I. Introduction

Technically-focused courses in engineering often neglect to consider the broader implications – social and environmental, for example – of technology designs. As part of a project funded by the National Science Foundation, our engineering school is working to find ways to incorporate values and practices relating to social justice, sustainability, humanitarian practice, and peace into undergraduate engineering education. The project's goals stem, in part, from a desire and need to find effective ways to fulfill ABET criteria, which require students to develop "an ability to apply engineering design to produce solutions that meet specified needs with consideration of... global, cultural, social, environmental, and economic factors" [1]. The project focuses on integrating technical and social content that cultivates sociotechnical awareness and practice among engineering students.

Educators have used a variety of strategies to incorporate social context in engineering education. Some researchers use the term "social justice" in connection with engineering to stress the importance of this larger context. Examples of this include Donna Riley's groundbreaking book in 2008 [2] and the book edited by Caroline Baillie, Alice Pawley, and Donna Riley on *Engineering and social justice: In the university and beyond* [3]. Jon Leydens and Juan Lucena present their Engineering For Social Justice (E4SJ) criteria for integrating engineering and social justice in curricula in their book [4] and Dean Nieusma has outlined strategies for reform [5]. Related curricular efforts have focused on entire classes such as Engineering and Social Justice [6] and Drones for Good [7] as well as modules within required engineering classes. This module and paper build most directly on work in undergraduate engineering education that developed modules relating to topics such as conflict minerals, material life cycle and social responsibility, and social context in heat transfer, and ethics in robotics [8-13].

In this paper, we show how considerations of social, environmental, and economic context were integrated into a required introductory course on electrical engineering for Integrated Engineering students. We describe the content, implementation, and evaluation of a "Design for the Future" module conducted in Spring 2019. We also show example worksheets that were developed for this module and that provide a framework for students to analyze and evaluate technologies, and for faculty to integrate non-technical context into their courses and evaluate students' engagement with this sociotechnical analysis.

II. Methods

A. Module Design

The "Design for the Future" module was developed by an interdisciplinary team of instructors, including the instructor for the class, a tenured professor in engineering with expertise in electrical engineering and materials science and two postdoctoral scholars, one with expertise in sociocultural anthropology and computer science and the other in bioengineering and learning experience design. We designed the module for an introductory course that focuses on electrical engineering for second-year students in Integrated Engineering. We designed the module to guide students through thinking about the implications of the design of technologies based on electric components. For example, these components rely on a variety of materials such as lithium and cadmium where mining, processing, or the recycling/waste of these elements have significant (often negative) social, environmental, and economic impacts. In thinking about these impacts, students are also guided to reflect on their role as engineers in designing technologies while considering these broader implications.

The module is framed around a course-long student project where students choose a technology of interest (TOI) to them that relates to electrical engineering, (e.g. Tesla batteries, solar cells, and tidal-powered turbines). The module consists of a project proposal, lectures, discussions and homework centering on materials and product lifecycle,

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an in-class exercise with worksheets to help students think more deeply about their TOI, and finally student presentations and reports. This module worked to fulfill two course learning objectives, namely that students are able to:

- Describe two examples of how electrical engineering topics from this course relate to their everyday lives.
- Describe an example of how engineers might consider social context in electrical engineering applications and why this is important.

The first learning objective was assessed qualitatively through the project proposals and presentations and reports, the second objective was assessed through in class discussion, worksheets, homework, and final presentation and reports. Six students participated in this course and module in Spring 2019. All students were invited to participate in the evaluation of the module and completed an informed consent form following university-approved Institutional Review Board (IRB) policies.

1) Project Proposals: In their first homework assignment of the semester, which also included preparing an introduction of themselves and analyzing simple circuits, students were asked to find a TOI and explain why it was interesting to them, how it relates to their lives, and do preliminary research that provided some initial facts about their TOI and consider unanswered questions that they still have. Students were asked to explain this in at least two paragraphs in the homework, as well as prepare two slides and present this information to the class.

Approximately one month later, building on feedback provided in the initial presentations, meetings with the primary instructor, and a first discussion about electronic materials centering on conflict minerals [10], [12], a second homework asked students directly to think about the social implications of their TOI. Students were to provide an updated summary of their TOI, as well as discuss the role of conflict minerals relating to their TOI and two other preliminary ideas about social implications relating to their TOI. These two homework assignments provide an initial foundation on which later discussions and exercises build for students to practice examining the multiple social, economic, and environmental impacts of technologies.

2) Electronic Materials Lectures & Discussions: In two subsequent classes and a homework, students were introduced to and further discussed the impacts of different materials, including lithium mining and hazardous waste. These lectures and discussions were framed around different phases in a product life cycle, focusing on early and end stages, namely materials & manufacturing and disposal & recycling. As engineers, students typically learn to focus on the Concept & Design phase, but teasing out different phases of the product life can help students think about different facets of a product that could affect a design, particularly in relation to questions of sustainability. The lectures also centered on examples of technologies that are popularly treated as sustainable and renewable, particularly electric cars and batteries and solar panels. The goal of these lectures was to expand students' understanding of what makes a technology fundamentally tied to electrical components more or less sustainable to help them think about ways that as engineers they can design for the future. Moreover, these in-class analyses of existing technologies familiarize students with thinking about their social, environmental, and economic implications in preparation of conducting similar analyses on their TOIs.

The lecture on lithium mining focused on the materials and manufacturing phase and discussed the definition of renewable energy according to US law, uses of lithium in contemporary technologies, the concentration of lithium in the "lithium triangle" in South America, a brief overview of the process through which lithium is extracted, and the political and economic context of lithium mining in different countries in the lithium triangle (Bolivia, Chile, and Argentina) [14]–[16]. The multiple actors and inequalities implicated in these contexts were highlighted, including the local environmental impact, the local (primarily Indigenous) communities that this affects, and those who gain economically including the employees, companies, and states. The lecture was concluded with a brief discussion of different ways that some negative impacts could be mitigated. For example, making lithium batteries more efficient would reduce the amount of lithium required, thus potentially reducing the environmental effects of lithium mining.

The lecture on hazardous waste focused on solar panels and the disposal and recycling phase and discussed the growth in solar panel use in the US, regulatory definitions of hazardous waste, and then focused particularly on Cadmium – a key component of some solar panels, discussing hazardous and non-hazardous levels of cadmium and research on cadmium leaching. This topic was combined with a homework assignment that asked students to write a memo to their (fictional) engineering manager where they outlined the advantages and disadvantages of using Cadmium Telluride (CdTe)-based solar panels for the development of a new solar farm, based on calculations of potential Cd leaching, as well as an evaluation of their assumptions, knowledge gaps, and what expertise would help them produce a better evaluation and design for the solar farm.

3) Worksheets: Building on the above, students participated in an in-class exercise designed to help them consider the design implications in relation to their TOI. The exercise included three worksheets seen in Fig 1, which spanned a product life-cycle: production, consumption, end of life. Each worksheet asked students to consider concerns relating People, Planet, and Profits for their technology and, particularly, who benefits, who pays, and who is excluded across these areas.

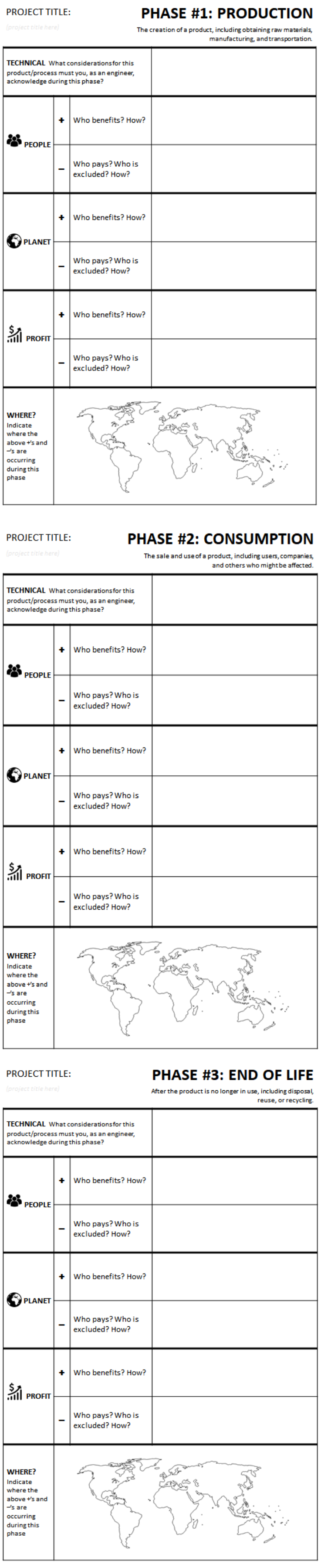

Fig. 1. Project worksheets for exploring social, environmental, and economic implications of a students' TOI.

The worksheets were posted on the wall around the classroom, and students were given markers to write on their worksheet. Worksheets were completed consecutively through the phases. For each worksheet, students were shown an example of one possible way to fill it out for a smartphone (which did not correspond to any student's TOI but had overlapping concerns with several of them). Students were then given 5 minutes for each worksheet to complete at least one box for People, Planet, and Profit and then finally to mark broadly on the map who benefits and pays globally. While students were completing their worksheets, the instructors circulated asking students to elaborate on particular points, clarifying any questions, and offering suggestions. Students kept their worksheets at the end of class to be used for their final presentations. The class concluded by discussing the complex distribution of benefits, costs, and exclusions globally for each phase, as well as asking students to choose and comment on which box on their worksheet they found most interesting with the idea that they could pursue those insights in more depth for their final project.

4) TOI Final Project: Finally, students presented on their TOI, examining the implications for design. Students were explicitly asked to describe both the technical function and operation of their technology, how it relates to topics in the course, and implications of their TOI drawing on the framework of People, Planet, and Profit. Following each presentation, students and instructors asked questions across the requirements for the presentation. Students were then asked to submit a report about their TOI a few days later, that covered the same requirements as the presentation but incorporated the feedback given in class.

B. Assessment

We used several ways of assessing how students were learning to examine the broader implications of their TOIs and of technologies and electrical components more generally. These combined qualitative and quantitative assessments and reflections. In particular, following in-class activities students completed a brief anonymous questionnaire about their experiences with the module component. Instructors also took extensive observations and reflections during and after the class to capture insights that students had learned and explore further areas of development in cultivating thinking about the implications of design. A focus group was also conducted by a colleague – a Professor of Sociology who was not a member of the teaching team – after students' final presentations, asking them to reflect on their overall experience with the course and module. Students' reflections from the focus group thus also cover modules on Conflict Minerals and a visit to an Electronics Recycling Center that complemented the Design for the Future module.

III. Student Response

Student feedback in surveys and the focus group showed that the module enabled students to think more deeply about the broader implications of technologies and their electrical components. We provide a reflection on the successes and areas for improvement of this module, along with the worksheets shown in Fig. 1, with the hope that they might help others incorporate them into their courses towards developing the capacity among engineering students to address broad considerations that support values such as sustainability and social justice.

Student reflections during the focus group highlighted how, through the TOI project, students learned the value of exploring the implications of design and connected personally with circuits. One student reflected on the diversity of topics in the course and the potential benefits for them:

> Honestly, I feel like this class was a lot cooler than the other regular circuits class cuz you get to go into a bunch of different things, and you don't dive as deep in stuff. Then, learning about things that are going on around the world that you would never have known if you were in just, probably just a normal circuits class, was cool. Then, this part [the presentations], whatever, probably wasn't fun, but you could say it was beneficial. It was researching something that you're into and then having to go in front of the class and talk about it?... It's not always the most fun thing to do, but if you look back at it, it's probably something that'll help us out for the future.

While the student, understandably, did not see presentations as "fun" they also recognized the benefit for the future they gained from the experience while also pointing out that they were researching "something that you're into." Another student reflected on how they learned to think about different aspects of circuits:

> Say, if I was designing something, maybe taking a more knowledgeable approach on what materials to use in the future, or where I'll be getting things from… Or just what I'm doing in general. I like how the class had different aspects into it… I'd rather take this class than the other circuits class by a lot.

Many student reflections in the focus group highlighted an ongoing tension between the technical content of the course and the focus of the module on the broader context. This tension reflects broader struggles in engineering and engineering education where technical content is often treated as more "rigorous" [17]. For example, one student suggested the technical skills they learned were more useful, but also suggested that they enjoyed doing research on a TOI:

> But I think the most helpful thing for me was learning the more technical skills. Like learning just like how to do calculations for all the electrical components. I also agree with them that it was really cool to do research on our own device and be able to present at the end of the semester.

The module, in some cases, was seen as something extraneous that was tacked on to the course:

> It's like it was a circuit class, and they were like, 'Oh, we gotta go in-depth on all these circuit things.' But then, they just randomly will bring in conflict minerals, and we'd just spend a day on that. Like in the middle of a circuit?... It felt very distracting and very just jumbled. If they had specific sections for it all, I feel like it would flow a lot bit.

Similarly a student commented:

> When we were taking the exam, it was a decent amount of questions that pertained to conflict minerals and writing about it in the exam. And that, at least, in my opinion, retracted from being able to reflect your knowledge of, actually, like calculations? And stuff like that?... It just, at least, for me, it prevented me from being able to study enough beforehand for other, like the more technical side of things?

Despite these tensions, students also concluded by highlighting the value of the broader discussions produced through the module and as part of this course for their futures as engineers:

> I'm going into sustainability… And in terms of what I wanna do after, this was a really strong starting point for that. Because I know in the next couple of years or so, I'm gonna start taking a lot of environmental science classes. A lot of sustainable engineering classes. So, this was like an intro to this class?... I felt like the overall of circuits and the conflict and the social implications was a good starting point for where I'm gonna go next. So, I feel like this was a really good time for this class to be just starting out. And for us to actually be in it. I feel like this was also the perfect semester for it.
>
> Yeah. I definitely agree with that since I'm going into the same major. It was definitely cool. Everything he said was exactly right. It was the perfect timing. And it made you realize a lot of things that you never really woulda thought of. Like you declare for sustainability, thinking it's really cool. That's what you wanna go into. But then when you're actually learning about some of this stuff, it actually makes you wanna do it even more.
>
> My concentration in this major isn't sustainability, but it was really cool to learn about it…. It's biomedical engineering. And that's actually what I liked about this class too because it really supported a bunch of different fields.
>
> So, for each of us, it helped us to learn a little more about the field that we wanna go into in the future. So, I thought that was really cool because it was truly integrated. Yeah. I think that was really cool.

That is, while students experienced a tension between their technical learning and the broader context, in thinking about their identities and futures they were enthusiastic about the "Design for the Future" module and other components of the course that focused on social context and social responsibility and appreciated the value of these facets of the course.

TABLE I. EXIT TICKET RESULTS FOR THE DESIGN FOR THE FUTURE MODULE FOLLOWING PROJECT WORKSHEETS

I think the material we covered in the Design for the Future module matters to me as an engineer (5-matters a lot, 1-does not matter at all)	**The way we learned about Design for the Future that was most valuable for me was**	**When we talked about Design for the Future in class, I felt (check all that apply)**
5	Project worksheets	Empowered, Excited, Curious
4	Classroom discussion	Empowered, Bored, Curious
4	Classroom discussion	Curious
3	Classroom discussion	Curious
4	Project worksheets, Classroom discussion	Excited, Curious

In terms of specific parts of the "Design for the Future" module, Table 1 shows the responses to the exit ticket conducted at the end of the worksheet class (prior to presentations and the final report). The exit ticket was completed by all five (out of six) students who were present in class that day. Corroborating the responses in the focus group, all students rated the material from the module from neutral to "matters a lot" in terms of how the "module matters to me as an engineer." The classroom discussion and the project worksheets, shown in Fig. 1, were the aspects that the students found most helpful in relation to the analysis of the broader implications of the TOI. When asked "When we talked about Design for the Future in class, I felt (check all that apply)" most students felt empowered, excited, or curious, although one student who marked curious also marked bored. Other options were depressed, angry, drained, or other. The focus on positive or forward-looking emotions is significant as students who leave the class feeling negative may be less inclined to value the attention to broader considerations. Four students left comments as part of the exit tickets (not shown in the table): "I think going through the lecture quicker would have been the best way to structure the class," "Worksheets were helpful to the project," "Forced me to think out the box," and "The project wkshts helped a lot ot [sic] think deeper." These highlight the ways that the worksheets integrated with the projects and helped students develop their thinking and students appreciated explore broader issues in relation to their TOI (rather than just through lectures).

IV. Instructor Reflections and Future Directions

One of our frequent observations about the "Design for the Future" module was how students were highly engaged in relation to their chosen TOI as a central focus for the module. Students who were quiet in general discussion often contributed when discussing their TOI. The TOIs also offered many concrete examples for us to draw on when discussing questions such as "what makes something sustainable?" and "how can we contribute as engineers to improving sustainability for technologies?." Their interest in their TOI was also reflected in their presentations where their excitement was clearly evident – more so in this aspect of the module than any other. This excitement had the additional benefit that other students were drawn in and were actively asking questions following the presentation. This excitement, however, also produced a tension for some students, where they were being asked to explore the, often negative, implications or effects of a technology that they found interesting or fascinating. In some cases, students found it difficult to move beyond their enthusiasm for a technology in order to think about it critically.

The worksheets were, however, effective, from the instructors point of view for helping students draw out different implications and interactions (positive and negative) relating to their TOIs. Students were able to think of considerations to include in most boxes, although the level of detail they were able to include varied. We played light instrumental music as students were working on their worksheets, which seemed productive for keeping the mood light even as they worked on intense and potentially oppressive topics. Students found the consumption phase the easiest to fill out, which is likely a reflection of it being closest to their direct experiences and what they are most used to thinking about. The worksheet divisions also led students to think about different ways their TOI could have an impact, including discussing what counted as an economic impact (Profit) versus a social impact (People).

On the latter point, the use of People, Planets, and Profits also produced some confusion in making such distinctions, despite the nice alliteration. In the future, we would revise to using Social, Environmental, and Economic as more precise distinctions. Keeping track of time while the instructors were busy engaging individual students was also a challenge, and in the future we would consider having a separate time-keeper or an automatic alarm for when to shift between phases. Another more substantive reflection regarding the worksheets is that the maps seemed an unnecessary but also insufficient to draw out nuances of geographic inequalities. While it could point to global flows of, for example, electronic waste to areas of the Global South, the details of economic inequalities within a country were easily lost. In the future, we would either separate this out into a separate activity altogether where students explore the different actors and relations of power involved in a particular phase in much closer detail, or remove it from the worksheets altogether.

While this module was offered for a small class, which allowed us to engage with individual students about their TOI, we believe the module would also be effective for larger classes. One way to implement this in larger classes would be for students to work in groups around a TOI. This would likely work to overcome some of the difficulties we experienced, such as students' over-enthusiasm about their TOI, as students within a group could challenge one another and explore multiple perspectives.

In implementing this module in the future, we also think it would be beneficial for students to explore one or two implications in more depth by drawing on relevant academic research in the social and environmental sciences. This would help cultivate a greater appreciation and understanding of the complexity of some of the implications. For example, many of the TOIs are built from electronic components assembled in factories in Asia. Research by anthropologists such as Aihwa Ong [18] have explored how these factories have both produced new economic opportunities and social status for young women, while also subjecting them to gender-based surveillance and exploitative labor practices in the factories where they work. Including such research-based analysis, combined with lectures and discussions about means of improving sustainability, would aim to foster a sense among students that they can contribute as engineers to improving technologies, but that solutions are rarely quick and easy, that multiple forms of interdisciplinary expertise can contribute to developing better technologies, while also analyzing what "better" means and for whom. Drawing out such examples thus might help students to have a deeper understanding of what is required and possible.

V. Conclusion

This module asked students to explore the broader implications of technologies based on electrical components. The module consisted of an extended project based on a Technology of Interest (TOI) for students and lectures, discussion, exercises, and assignments to leading students to examine the social, environmental, and economic contexts of their TOI and of sustainable technologies more broadly. The focus on a TOI worked to engage students based on individual interests and students found the module helpful for thinking deeper about these broader contexts in ways that they found valuable to their future careers as engineers. Future work will include incorporating research-based analysis from the social and environmental sciences.

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