SUSTAINABLE SYSTEMS ENGINEERING PROGRAM: MEETING ALL NEEDS WITHIN MEANS OF THE PLANET

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ABSTRACT

Across engineering education in Canada and the world, there is an increased recognition of the importance of sustainability mindsets, particularly since the adoption of the Sustainable Development Goals in 2015. Traditionally, sustainability within engineering has focused on the technical issues and taken a very end-of-the-line approach, for example looking at how to technically manage and reduce pollution (Tejedor et al., 2019). There is a growing recognition of the need to transition to a more holistic systems approach to more effectively address sustainability by considering the "complex, systemic interconnections and cause and effect relationships" (Sandri, 2013). This is also reflected within the CDIO Syllabus 3.0 section 4 which highlights the importance of systems engineering within societal and environmental contexts. At the University of Calgary, we developed a program in sustainable systems engineering from the ground up, where we intentionally imbedded a systems approach and a regenerative design mindset from the onset. In this paper, we provide an overview of the frameworks we have used to guide our program development. For example, the *engineering for one planet framework* (EOP, 2020) aims to "minimize negative impacts, strive to achieve at least net neutral outcomes, and, ideally, are restorative" (p.9). If we are to be truly transdisciplinary in our approach to solving complex challenges, we need to move from a human-centered to a life-centered approach. Overall, we hope to foster mindsets to develop engineering students who are able to fundamentally shift the discourse on sustainability engineering within industry, and critically reflect on the role of engineering itself. As engineers our responsibility is not only to society and culture, but also to nature and the planet. This program aims to provide students with the necessary skillsets to foster real change across engineering industries to better support the interrelated elements of our society and planet.

KEYWORDS

Sustainability, Systems, Engineering for One Planet, Environmental Justice, Program Development, Standards 3, 5, 7

INTRODUCTION

There are many calls to change sustainability education in engineering, and these calls are continuously becoming more urgent. As expressed in a recent Journal of Engineering Education editorial, it has become more evident that we need a fundamental change to the way we teach engineering. Specifically, engineering education needs (1) to acknowledge that engineering design is directly linked to the climate; (2) to be more interdisciplinary; (3) to take a social justice approach to engineering; and (4) to co-create with diverse communities (Martin et al., 2022).

Sustainability education in engineering has rapidly increased over the last couple decades (Thürer et al., 2018), although much of this education focuses on economic and environmental sustainability, with little focus on social sustainability (Reynante, 2022). Even the most successful efforts in integrating sustainability across a curriculum still find barriers on sustainability being considered a “soft” skill that is not valued in engineering, and no one willing to take ownership over the sustainability content. Reynante (2022) provides a clear outline in their comprehensive literature review of the continuing mindsets and ideologies that marginalize sustainability efforts in engineering education which include: positivism and objectivity, reductionism, technical-social dualism, techno-solutionism, and consumerism and materialism.

The CDIO syllabus also recognizes the importance of this change in mindset towards the way we teach engineering, including the following examples within section 4 (the innovation process) of the CDIO Syllabus 3.0 (Malmqvist et al., 2022; CDIO, n.d.):

- 4.3.1 Needs vs. wants with respect to justice and sufficiency
- 4.3.1 Understanding conditions for operating within planetary boundaries
- 4.4.6 Design for Circular Economy

There are many approaches to change in engineering education (see Reynante, 2022). At the University of Calgary, we developed and are now implementing an entire new program called the Sustainable Systems Engineering Program (Paul et al., 2021, Paul & Eggermont, 2022). In this paper, we will provide a discussion of our rationale and mindsets in the development of the program, as well as an overview of the program design.

BACKGROUND LITERATURE

Integral to the design of the new sustainability program was incorporating literature that informed the mindsets across the program curriculum. Specifically, here we discuss the Engineering for One Planet framework, and the importance of integrating justice approaches.

Engineering for One Planet

“Principles of Environmentally Responsible Engineering: Creating a Roadmap for Change” was a roundtable attended by the author in 2019 which led to becoming a contributor to an initial Environmentally Responsible Engineering (ERE) Definition and Framework to being a member of the Engineering for One Planet (EOP) Design Team from 2020 to 2022. Now known as the EOP framework, it is defined as follows:

> The EOP framework outlines the cross-cutting knowledge, awareness and competencies needed to design, build, manage and implement engineering solutions that minimize negative impacts, strive to achieve at least net neutral outcomes, and, ideally, are restorative. EOP will enable engineers to be better equipped to create positive outcomes for the planet and the life it sustains, now and for future generations, and to help ecosystems recover and thrive when possible. Rather than a new discipline, EOP comprises the fundamental

> learning outcomes that every graduating engineer —regardless of subdiscipline, institution, identity, or geography— needs to acquire to excel as engineers operating within our planet's constraints. By possessing the basic knowledge, understanding, skills, experiences and behaviors of EOP, future engineers will be prepared with the competencies to ensure that engineering disciplines do not inadvertently harm but seek to enhance the well-being of humans and the living planet. (EOP, 2020)

The EOP framework (see Figure 1) has systems thinking at its core teaching students the ability to identify and understand interconnectedness and how all human-made designs rely upon and are embedded within ecological systems. In addition, it touches on feedback loops, tipping points, and system resilience. The program aims to foster students with the skillsets necessary to consider outcomes of present engineering design decisions on future generations. In understanding tradeoffs and identifying impacts between different parts of the system it reminds one of Kate Raworth’s Doughnut Economics (Raworth, n.d.), meeting the needs of all (the social foundation) within the means of the planet (the ecological ceiling).

The framework includes skills recognizable for any engineering program such as leadership, teamwork, and critical thinking, all while emphasizing the role of environmental responsibility. Design, materials choice, and environmental impact measurement are listed as key technical skills but pays attention to understanding environmental and social impacts of others’ designs and setting goals to minimize environmental impact. Where it expands most on current engineering curriculum is in the knowledge and understanding category of the framework. Environmental literacy, responsible business and economy, and social responsibility in this domain add several interesting and relevant education pieces for future engineering students. Advanced concepts such as an awareness of key environmental laws, ethics and policies at the regional, national, and global levels, an ability to consider ethical implications beyond current compliance and political boundaries, and knowledge of ecosystems services are a few of the key knowledge-based pieces that the framework recommends in order to educate a new breed of engineers.

New business models, such as models that leverage product durability are closely tied to design and encourages teaching design for circularity. The 9Rs (which may be up to 12 now) help to promote the idea of circularity: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle (Khaw-ngern et al., 2021). This, along with an awareness of emerging economic systems intended to promote environmental and social responsibility in economic thinking ties back to systems thinking and doughnut economics.

Our students need to be aware as global citizens of social and cultural implications related to local, regional, and global materials use and learn to recognize that impacts are disproportionately borne by low income and minority groups.

Current and past engineering mindsets and ideologies that marginalize sustainability will have to start taking a backseat if we want our species to survive. This includes - among other mindsets - not perpetuating the current techno-social dualism and techno-solutionism: that the social is irrelevant and the belief that technology can unilaterally solve complex social and environmental problems (Reynante, 2022). Time to leave the comfort of the quantifiable and dip our toes in the messy, unreliable, data-skewing externalities of the qualitative.

Figure 1. Engineering for One Planet framework (EOP, 2020)

Environmental Justice in Engineering Education

Around the world there are many examples of how engineering has played a significant role in environmental degradation that disproportionately impacts black, indigenous, and other minoritized identities. For example, even though Shoal Lake has provided drinking water for the city of Winnipeg for over a century, it wasn't until 2021 that the Shoal Lake 40 First Nation's community was provided with safe drinking water. Not only that, but the engineering decisions making an aqueduct at Shoal Lake isolated the indigenous community making it impossible for them to travel (Perry, 2016). In the United States, the Flint water crisis is another example where since 2014 elevated levels of lead have been found in the water system due to engineering decisions and mistakes (Masten, Davies & Mcelmurry, 2016).

These are only two examples of how essential of a role engineers play in environmental justice, and how traditionally these social justice considerations have been left out of engineering decision making. Rather a “path of least resistance” approach is typically taken during engineering problem solving, which tends to impact minority and poor communities most negatively (Ramirez-Andreotta, 2019). Not only this, but analysis has shown that engineering education has had very limited adoption of environmental justice education compared to other departments, even though engineering has been such a significant contributor to environmental injustices (Wilson-Lopez, Taylor & Santiago, 2022).

Through our program design we hope to learn from scholars in the area who are integrating environmental justice into engineering education using intentional pedagogies (Wilson-Lopez et al., 2022; Bielefeldt & Silverstein, 2021). Many have begun to understand the importance of systems thinking in the context of sustainability in engineering and social justice in engineering (Martin et al., 2022; Reddy & Mancus, 2021). Additionally, there has been much discussion on the importance of project-based learning and community-based learning as transformative learning pedagogies to support the development of the necessary skills in sustainability engineering and environmental justice (Faludi & Gilbert, 2019; Reynante, 2022).

PROGRAM DESIGN: SUSTAINABLE SYSTEMS ENGINEERING

“I hope you are doing well and enjoying the nice weather! I was hoping to grab a bit of your time to chat about sustainability initiatives.” This innocent email from September 2020 started a 2-year design deep dive and resurfaced as a new undergraduate major which will welcome its first cohort in September of 2023. An interdisciplinary group representing all engineering departments including undergraduate and graduate student representatives was tasked with designing a ‘lean’ sustainability program. We accomplished this by integrating core engineering courses from across the school and integrating among other things sustainability principles, regenerative design, and land-based and experiential learning:

1. Systems thinking (Holistic Principle)
2. Respect for energy & natural resources (Conservation Principle)
3. Respect for people (Human Vitality Principle)
4. Respect for place (Ecosystem Principle)
5. Learning from natural systems (Biomimicry Principle)
6. Respect for future (“Seven Generations” Principle) “In our every deliberation we must consider the impact of our decisions on the seventh generation.” (McLennan, 2004)

In addition we created a design for sustainable systems spine that runs through all four years of the program. This is in line with CDIO Standard 5 which emphasizes the importance of Design-Implement experiences. Specifically, CDIO Standards supported understanding of the importance of structuring the courses as sequential learning experiences to reinforce students’ learning at increasing levels of complexity.

A full curriculum is shown in Figure 2, and in this section we will provide a broad overview of each year of the program, as well as highlight unique courses which we believe showcase the incredible interdisciplinary program design that aims to change the culture and beliefs around sustainability in engineering.

YEAR 1	
FALL TERM	WINTER TERM
CHEM 209: General Chemistry for Engineers	ENGG 201: Behaviour of Liquids, Gases and Solids
MATH 211: Linear Algebra 1	PHYS 259: Electricity and Magnetism
MATH275: Calculus for Engineers and Scientists	MATH 277: Multivariable Calculus for Engineers
ENGG 225: Fundamentals of Electrical Circuits and Machines	ENGG 202: Engineering Statics
ENDG 233: Computing for Engineers	ENGG 200: Engineering Design and Communication
	Complementary Studies Course I
YEAR 2	
FALL TERM	WINTER TERM
SUSE 301: Sustainable Systems Ecology	
SUSE 315: Engineering economics and decision making for sustainability	CHEM 321: Environmental Chemistry
ENDG 319: Probability, Statistics and Machine Learning	SUSE 311: Engineering Thermo-dynamics and fluid mechanics
MATH 375: Differential Equations for Engineers	ENGG 349: Dynamics
ENCI 317: Mechanics of Solids	SUSE 303: Signals, Instrumentation, and Data
SUSE 307: Numerical Methods and Computing Tools for Sustainable Systems Engineering	SUSE 300: Introduction to Sustainable Systems Design
AUGUST FIELD SCHOOL	
SUST 403: Sustainability Research Methods	
SUSE 401: Remote Northern Sustainable Systems *or* SUSE 403: Northern Sustainable Systems	
YEAR 3	
FALL TERM	WINTER TERM
SUSE 409: Regenerative Design Principles and Indigenous Knowledge Systems	ENEL 487: Electrical Engineering Energy Systems
ENEE 355: Introduction to Energy and the Environment	ENEE 575: Renewable Energy Systems
ENCI 481: Environmental Engineering	ENME 461: Foundations of Mechatronics
ENGG 461: Geospatial Data Analytics	SUSE 463: Systems modelling, Simulations, and analysis
Complementary Studies Course II	SUSE 400: Design of Sustainable Systems
YEAR 4	
FALL TERM	WINTER TERM
ENEE 503: Life Cycle Assessment	ENGG 502: Capstone
ENGG 481: Technology and Society	ENGG 513: The Role and Responsibility of the Professional Engineer in Society
ENGG 501: Capstone	Engineering Technical Elective
Approved SUSE Program Course	Engineering Technical Elective
Approved SUSE Program Course	Approved SUSE Program Course

Figure 2. Sustainable Systems Engineering curriculum

Years 1 and 2 of the program are a foundation for engineering and sustainable systems. This builds on many existing courses, as at our institution, all first-year courses are common, and many second-year courses are common to provide students with foundational engineering knowledge and skills.

Although at first glance, there is perhaps a feeling of the curriculum being a crash course in all engineering subjects, we want to highlight two intentional choices behind this design. Firstly, the goal of the program is to create a broad knowledge foundation focussed on the “system of engineering”. By broadly covering topics from all disciplines we are able to achieve this. Additionally, we are able to tied together the varied disciplines into the life-centered sustainable systems view through the design spine courses (most notable SUSE 300 and SUSE 400), and the SUSE core courses (SUSE 301, 401/403, 409 and a number of 500-level technical electives). Secondly, a long term goal is to infused the worldview across all disciplines – so although students in the SUSE program will specialize in sustainable systems, we want all graduates (electrical, mechanical, chemical, etc.) to take courses which emphasize life-based sustainable systems approaches. By collaborating with the departments across the engineering faculty in creating SUSE required courses, we hope to achieve this.

SUSE Specific Courses

In between years 2 and 3 students can take a *Remote Northern Sustainable Systems* field course in which they learn key ideas and strategies related to environmentally sustainable community development with a focus on food, water, and energy. Through pattern and data mapping, research and data analysis, and site visits, the students in the field course will explore community needs and the challenges of environmentally conscious living. The renewable energy systems at the field station will be investigated along with energy usage. Learners delve into the common misconceptions that lead to unsustainable social practices and how to counteract these fallacies through community education and engagement. A second option, *Northern Sustainable Systems*, teaches key ideas and strategies related to environmentally sustainable community development with a focus on net zero communities and geo-powered communities, exploring renewable energy systems at various sites and integration into local and community energy networks. These integrated learning experiences (CDIO Standard 7) will allow students to apply their professional and technical engineering knowledge, while simultaneously building personal, interpersonal, and systems thinking skills.

Year 3 is in preparation of SUSE themes which require knowledge, awareness and competencies needed to design, build, manage, and implement engineering solutions that minimize negative impacts, strive to achieve at least net neutral outcomes, and, ideally, are restorative. Students continue to take courses that are interdisciplinary, so as we move into implementation of these courses, it will be essential to ensure the curriculum remains integrated and students are able to understand the disciplinary linkages (CDIO Standard 3: Integrated Curriculum).

In year 4, students can tailor their program and focus on one of four themes:

- Sustainable systems for Environment
- Sustainable systems for Communities and Cities
- Sustainable systems for Energy and Resources
- Sustainable systems for Food, Agriculture, and Biomass

There are three courses which highlight the unique aspects of the SUSE program and its design. Firstly, the *Sustainable Systems Ecology* course is taken at the beginning of year 2 which introduces students to upper year possibilities and is a preview of the four theme areas. This short 5-day course is an introduction to macroecology for sustainable systems, including theory, tools, and techniques. It introduces students to systems thinking and program theme areas through design projects and ‘campus as a learning lab’ workshops.

Another course highlight is the *Introduction to sustainable systems design* course which students take in their second semester of year 2. This course introduces students to systems thinking, design for a circular economy, tools for sustainability and regenerative engineering, and concepts of design for justice. The course uses collaborative and creative practices to address the deepest challenges our communities and environments face, centering on the voices and habitats of those who are directly impacted by the outcomes of the design process. In addition, systematic design methods are introduced as part of community-engaged projects.

Finally, a particularly unique course is a non-standard course (meaning a concentrated one-month schedule) called *Regenerative Design Principles and Indigenous Knowledge Systems.* In this course, students will explore principles of regenerative design and systems thinking through an Indigenous Knowledge Systems lens, and whole systems thinking to create resilient and equitable systems that integrate the needs of society with the integrity of nature. Topics that will be explored are grounded in Indigenous methodologies and epistemologies and explore Indigenous Knowledge and the intersection of sustainability science in a culminating land-based learning experience.

CONCLUSION

Overall, we hope to foster mindsets to develop engineering students who are able to fundamentally shift the discourse on sustainability engineering within industry, and critically reflect on the role of engineering itself. As engineers our responsibility is not only to society and culture, but also to nature and the planet. This program aims to provide students with the necessary skillsets to foster real change across engineering industries to better support the interrelated elements of our society and planet. We aim to accomplish this both through using theoretical foundations in the development of the program, including Engineering for One Planet framework and environment justice, and applying unique pedagogies to the courses. Long term, we hope by co-creating these courses with disciplines from across the engineering faculty, that the life-centered engineering worldview core to the SUSE program will begin to be integrated and fundamental to other engineering programs as well. The first set of students will be entering the program in Fall 2023, and we look forward to co-creating transformative learning experiences with them.

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BIOGRAPHICAL INFORMATION

Robyn Mae Paul is a PhD candidate in Mechanical Engineering at the University of Calgary. Her teaching and research integrates principles from ecofeminism to deconstruct the hidden curriculum of engineering education. She is passionate about student mental health and creating new narratives of engineering that centre social and environmental justice conversations.

Marjan Eggermont is an artist, Associate Dean Sustainability, and Professor (Teaching) in the Schulich School of Engineering at the University of Calgary. In 2003 she was named one of the 20 most influential artists in Calgary by the Calgary Artwalk Society. She is a Biomimicry Institute Fellow and has been working in the field of bio-inspired design since 2004 with a focus on visualization and abstraction. She co-founded and designs Zygote Quarterly (zqjournal.org), an online open-source bio-inspired design journal to provide a platform to showcase the nexus of science and design using case studies, news and articles. She holds a BA, BFA, and MFA and finished a PhD in Computational Media Design focusing on bio-inspired information visualization in 2018 at the University of Calgary. For the past 6 years she has volunteered with NASA VINE as part of the Education research working group to explore nature-inspired technology.

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