Strategies for embedding engineering for sustainable development in undergraduate teaching

Strategies for Embedding Engineering for Sustainable Development in Undergraduate Teaching

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Abstract

The significant challenges of sustainable development necessitate that we equip the next generation of engineers with the skills, knowledge, and values needed to mitigate climate change, manage global risks, and design a more sustainable, resilient, and equitable future. Professional organizations and NGOs have echoed this call via initiatives and accreditation requirements. Similarly, researchers have already defined the student competencies, pedagogies, and conceptual frameworks needed to support the integration of engineering for sustainable development (ESD). Moreover, numerous case studies describe innovative actions already taken at universities around the world, but they have not yet been synthesized into a generalizable methodology for embedding ESD. Through a thematic literature review, a key gap has been identified: the lack of a comprehensive, literature-based approach that defines a clear path for individual professors to embed ESD. Thus, this study asks: What are the key strategies that instructors could use to embed ESD in core undergraduate engineering courses?

This study adopted an iterative methodology involving engaging with case study literature and learning directly from the lived experience and current efforts of professors working to integrate ESD. The pedagogies, approaches, and insights identified were synthesized into a list of strategies. In total, 20 participants were involved across two phases of interviews: scoping and validation.

The presented strategies define an explicit, actionable pathway for any motivated instructor in any engineering discipline to fulfil their teaching of accreditation-required technical content in ways that simultaneously support the development of ESD competencies. This bottom-up approach allows professors to learn from the case studies already available and act immediately, independent of resource-intensive, top-down university programming.

1 Introduction

Engineering education for sustainable development (EESD) involves training engineers to be holistic, systems-based, multidisciplinary, future-focused problem solvers (‘Declaration of Barcelona’, 2005). It requires working across disciplinary boundaries, understanding and influencing policy, and engaging with stakeholders and end users (ibid.). This requires an essential shift from recognizing sustainability as one of many constraints of the design process to instead embracing it as the context in which engineers must always operate (Byrne, 2023).

Over the past 25 years, academics have recognized this need, and momentum towards EESD has grown significantly (Narong and Hallinger, 2024). Declarations have defined the key engineering for sustainable development (ESD) competencies required of engineers ('Declaration of Barcelona', 2005; Fenner & Morgan, 2021), and researchers have both theoretically and empirically identified the instructional pedagogies that support the development of these competencies in students (Lozano *et al.*, 2017; Tejedor *et al.*, 2019). Professional organizations have also contributed, integrating sustainable design criteria into the accreditation requirements that shape engineering education (Byrne, 2023).

These critical pedagogies and concepts are already being implemented, generally through top-down initiatives like the development of new degree programs (Lozano & Lozano, 2014), designing new courses (El-Zein *et al.*, 2008), professional development courses for instructors (Pérez-Foguet & Lazzarini, 2019) and large-scale curricula renewal (Weatherton *et al.*, 2015). However, engineering curricula are already overloaded (Guerra, 2017) and renewing curricula requires significant effort and can take years (Gutierrez-Bucheli *et al.*, 2022), while elective courses and new degree programs only reach a minority of students (Sánchez-Carracedo *et al.*, 2021). Therefore, to act urgently and comprehensively, instructors must instead embed ESD concepts into existing courses (Pérez-Foguet & Lazzarini, 2019). This flexible, bottom-up approach is the most holistic and versatile pathway for EESD because it reaches all students, can be applied within existing program structures, and provides contextualized learning opportunities. Thus, this paper proposes practical strategies for embedding ESD in existing courses, so that all engineers can develop the competencies needed to tackle the sustainable development challenges of the 21st century.

2 Methodology

A multi-step thematic analysis methodology was employed to synthesize strategies for embedding ESD. This methodology, summarized in Figure 1, is consistent with other studies focused on developing action-oriented strategic frameworks (Blizzard & Klotz, 2012; Corsini & Moultrie, 2019).

First, one-hour semi-structured scoping interviews were conducted with a small set of experts to understand the lived experience and current efforts of professors working to integrate ESD. This involved five engineering professors at institutions in Australia, Ireland, New Zealand, the United Kingdom, and the United States. Each participant had extensive experience directly teaching or embedding ESD concepts in their various fields of engineering expertise, which included chemical, civil, materials, and health/social justice. During the interviews, participants were asked about their background, perspectives of EESD, their experiences with integrating ESD concepts, and barriers they have faced.

A literature review revealed that a significant number of case studies describing specific courses or programs are available. To build on this broad foundation and ground the recommended strategies in the existing body of literature, a review of published case studies was conducted. This case study review was scoped to only include peer-reviewed journal and conference papers written in English describing detailed cases of teaching ESD. The five exploratory interviews and 51 papers were then thematically analyzed in a multi-step process defined by Braun & Clark (2006) using Process and Concept coding methods described by Miles *et al*. (2020). The resulting codes were iteratively combined to form 24 methods grouped into eight preliminary strategies.

The preliminary strategies were then tested through 16 validation interviews with a diverse set of experienced engineering instructors who were passionate about sustainable development and were comfortable being interviewed in English. Participants were identified through personal networks. Collectively, the participants teach or taught at 15 different universities on five continents and had a range of experience with the topic, ranging from novice (passionate about sustainable development but have never addressed it directly in their teaching) to expert (20+ years of experience teaching or integrating ESD). This diverse range of experience levels, disciplines, and institutions was helpful for identifying gaps and validating the generalizability of the strategies.

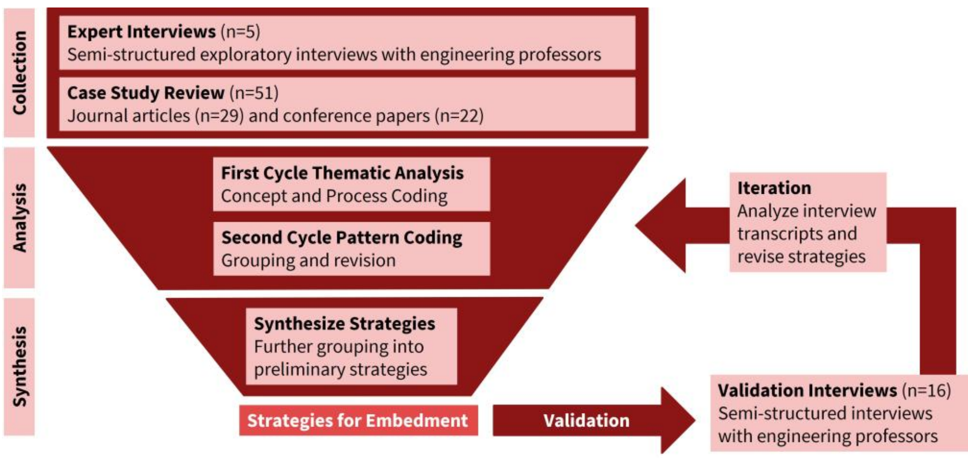

Figure 1: Summary of methodology

3 Findings

Six specific strategies and two cross-cutting strategies for embedding ESD in existing courses were identified. Figure 2 provides a graphical overview of the strategies, laying out how they can be applied to transform traditional engineering teaching into EESD. Each of these strategies is then broken down into three specific methods (summarized in Table 1) which provide more detailed directions for applying the strategies. The following sections summarize the findings, which are fully described in Burlotos (2024) alongside discipline-specific examples and a discussion of potential barriers.

3.1 Anchor ESD

The first step in embedding ESD is to formally anchor it as a critical component of the course. The most practical way to begin anchoring ESD in traditional engineering teaching is to put it in the syllabus. This communicates ESD's critical role in the course to the students and builds a strong foundation from which learning activities can be developed.

3.2 Call Out ESD

Once ESD is anchored in the syllabus, it must be frequently referred to. The two strategies in this category are about making it explicit for the students, continuously reinforcing that ESD is a critical part of engineering education that permeates all areas. First, contextual learning helps students make meaningful connections between purely technical concepts and the real-world settings in which they are applied (Guerra, 2017). As one participant noted, when presented with relatively abstract mathematical concepts, students tend to think "*Who cares?*" or "*Why do I need this?*" which presents an opportunity to contextualize it with ESD-themed topics like risk-informed decision-making, helping "*both their sustainability education…[and] their [mathematics] education."* Another strategy for bringing ESD to the forefront is to explicitly define it and connect it with existing course content.

3.3 Actively Apply ESD

The next step is to develop the competencies in the students through active learning activities. This category consists of three strategies. First and foremost, students must learn to critically evaluate the sustainability of various engineering solutions. Next, instructors can build off pedagogies commonly applied to develop ESD competencies: project-oriented learning, project-based learning, and community-based learning. The last strategy in this category is to prepare students for sustainability-focused careers by engaging with ESD content in ways that mimic its application in industry.

3.4 Cross-cutting Strategies

While synthesizing the strategies, two cross-cutting strategies emerged that permeate through the others. First, establishing ethos (credibility) is critical to delivering an effective message. It is imperative that when introduced to ESD-related content, students perceive it as critical information coming from a reputable source. Second, leveraging pathos (emotion) involves connecting with students' experiences and values to foster deeper engagement with the material. Taking action towards ESD is a complex and difficult endeavor, so intentional inspiration and empowerment is critical to developing the next generation of change agents.

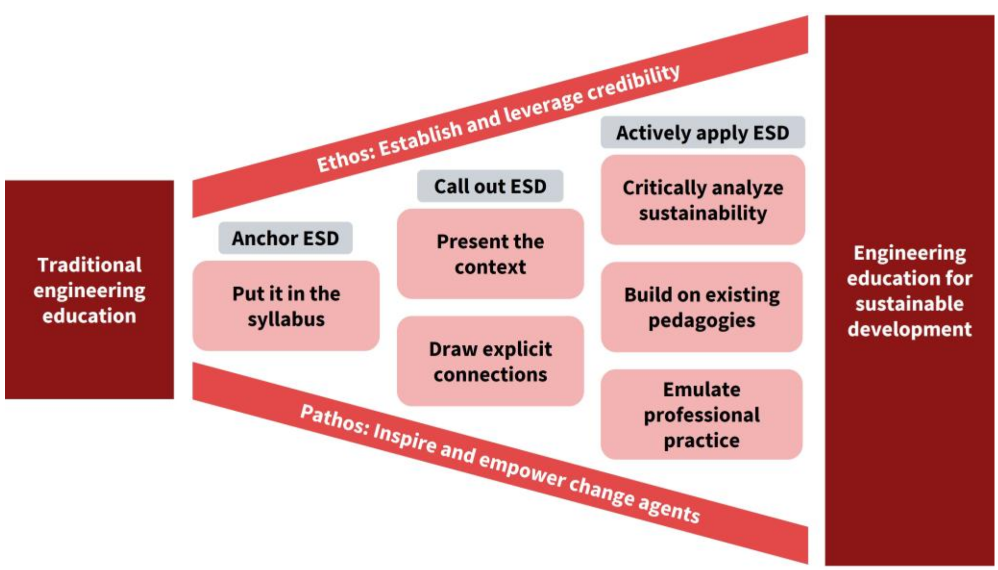

Figure 2: Overview of strategies for embedding ESD

Table 1: Summary of strategies for embedding ESD

Anchor ESD			
1	Put it in the syllabus	1.1	Update learning objectives to include relevant ESD competencies and concepts
		1.2	Assess ESD-related activities and factor them into students' grades
		1.3	Consider and map ESD-related accreditation requirements and apply them in your course
Call out ESD			
2	Present the context	2.1	Place technical content within ESD context
		2.2	Consider non-technical landscape – social, environmental, economic
		2.3	Apply real-world case studies and examples with complex ESD implications
3	Draw explicit connections	3.1	Define key ESD concepts/competencies and call them out as they arise
		3.2	Thoughtfully map content to key Sustainable Development Goals
		3.3	Connect with topics that students are already familiar with or interested in
Actively apply ESD			
4	Critically analyze sustainability	4.1	Evaluate the societal impact of engineered systems/products using the triple bottom line approach and acknowledge uncertainty in analysis and projections
		4.2	Challenge dominant ideas by considering and evaluating alternative solutions, both technical and non-technical, from various perspectives
		4.3	Acknowledge and assess the trade-offs of possible solutions to complex, non-optimizable problems
5	Build on existing pedagogies	5.1	Add an ESD component to projects and/or frame projects around ESD topics (e.g., project-based learning)
		5.2	Utilize open-ended 'wicked' problems, require students to select and define problems themselves, and/or incrementally increase complexity of traditional content by gradually adding ESD factors (e.g., problem-based learning)
		5.3	Work on real-world problems with local or global organizations to contextualize technical skills and ESD competencies (e.g., community-based learning)
6	Emulate professional practice	6.1	Study technical ESD concepts directly, where appropriate
		6.2	Apply industry-standard tools and procedures in the classroom
		6.3	Mimic real-world complexity with role plays, games, and multidisciplinary teams
Cross-cutting strategies			
7	Establish and leverage credibility	7.1	Anchor ESD material to traditional engineering by establishing continuity between courses and leveraging instructor's position as a technical and/or professional expert
		7.2	Acknowledge the interpretive nature of ESD concepts and contrast it with the traditional approaches to engineering design decisions
		7.3	Link ESD concepts to professional practice by leveraging guest speakers
8	Inspire and empower change agents	8.1	Mitigate eco-anxiety and hopelessness by referencing positive case studies and focusing assignments on developing solutions to ESD problems
		8.2	Encourage students to engage with each other and critically reflect
		8.3	Responsibly consider engineers' role in the cause of, and potential contributions towards collaboratively alleviating, inequities in vulnerable contexts near and far

4 Discussion

While the strategies define a logical workflow and rigorous systematic approach to ESD integration, they could also be implemented independently and to varying degrees. For instance, they could be applied in a complete course redesign or simply to augment existing content with ESD components. Similarly, while Figure 2 depicts a linear process with a defined start and finish, instructors should embrace a "*continued progression of thinking about pedagogical approaches…in new and iterative ways*." However, it is important to "*not overdo it*," as not all strategies are suitable for all classes. As one interviewee noted, "*if you just start throwing things into a course [and] it's not well thought out, they become Frankenstein courses."* One professor who uses multiple case study assignments in their course noted that it might be better to completely change one assignment to explicitly deal with sustainable design rather than slightly modify each case study. This also eases the workload for the instructor, as preparing "*one lecture or one activity is likely to be more possible…than trying to embed too many things in a single course.*" In summary, the strategies are not a checklist; professors must ask themselves what fits best in their course.

When applying the strategies, it is also important to note their interconnectedness. The strategies and methods themselves are not mutually exclusive, with multiple repeating similar themes. For example, life cycle analysis could be applied in Methods 4.1, 5.1, 6.1, and 6.2. Similarly, single assignments can target multiple strategies. One notable example identified in an interview that combines all three methods in Strategy 5, as well as elements of Methods 2.2, 3.3, and 6.3, is a semester-long community-based learning project where students identify a community partner, pick a topic, and define the problem before spending seven weeks carrying out an engineering design. Other notable and more accessible examples of cross-cutting assignments identified in the literature include a brake pedal design project with strong ESD integration (Ramanujan *et al*., 2019) and a linear algebra assignment framed around a hypothetical dam (Pérez-Foguet & Lazzarini, 2019). These examples serve as models for applying the strategies in traditional engineering design and engineering science courses.

While the proposed strategies are a comprehensive pathway for integrating ESD and consist of 24 methods targeted at different elements of the teaching process, their underlying principles are surprisingly simple. One interviewee succinctly summarized that the strategies are *"not about adding more content, but…revising the content that you [already] have*." This is a critical realization, as most course syllabi are already overcrowded. Similarly, another participant noted the importance of "*deliberate[ly] and conscious[ly] talking about sustainability…[and] making it more forefront,*" which echoes the recommendations to anchor and call out ESD. Seeing a practical pathway motivated professors researching ESD-related topics to see the importance of similarly embedding ESD in their teaching. One participant initially admitted that ESD is "*not something I've deliberately thought about incorporating into my teaching*" but later acknowledged that because of the conversation, ESD is now "*at the back of my mind…I need to pay more attention to it."* Lastly, recognizing that there is "*always room…for improvement and evolution*," one expert interviewee noted the importance of treating *"your course as a laboratory*" and constantly iterating to improve course materials.

5 Conclusion

This paper presents strategies for modifying traditional engineering teaching to simultaneously support the development of ESD competencies. Urgent global environmental, social, and economic threats require that holistic, systems-based, multidisciplinary, future-focused problem-solving be a central component of every engineer's education. Recognizing that engineering curricula are already overcrowded, these strategies fill a critical gap by defining an explicit, bottom-up pathway to integrate ESD in core courses, enabling immediate action through existing structures that reach all engineering students. While previous studies have defined conceptual frameworks, specific pedagogies, and student competencies, this study builds on these to provide actionable strategies for embedding ESD in any engineering discipline. To ground the strategies in existing best practices, they were synthesized from findings across 51 published case studies and 20 interviewees.

Professors applying these strategies should consider several key recommendations. Depending on the context of the course and the professor's goals, the strategies can be applied collectively or individually. They are not a checklist; professors should critically reflect on what fits best in their course. Often, ESD is already implicitly present in courses without the students, and perhaps even the professor, noticing. These strategies can assist in identifying key links and explicitly communicating the connections between the course content and sustainable development. Applying the strategies is not necessarily a linear process, nor must it begin at square one. Professors at any stage of their ESD integration journeys could apply these strategies to improve their students' ESD competencies. Not unlike sustainable development, as one expert aptly observed, "*education by its nature is a complex, iterative, messy problem*" which requires a creative, holistic, and multi-disciplinary approach. By applying these strategies and cementing ESD as an integral component of their education, we can equip the next generation of engineers with the skills, knowledge, and values needed to urgently tackle 21st-century challenges and promote sustainable development.

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