Engineering for One Planet
Literature Review Report

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EXECUTIVE SUMMARY

The Engineering for One Planet (EOP) initiative is working to transform engineering education to enable all future engineers to be equipped with fundamental principles of sustainability. This report synthesizes key findings from a literature review that focused on identifying systemic barriers, strategies, success factors, and models relevant to integrating sustainability into engineering curricula. Historically, sustainability has been marginalized within engineering and engineering education due to a variety of ideological and institutional factors. However, the last two decades have witnessed a rapid increase in the number of engineering schools around the globe—particularly in Australia, Europe, and North America—that have incorporated sustainability courses and modules. Yet despite this surge of activity, few institutions have thoroughly embedded sustainability throughout their curriculum, and there is little evidence that most engineering students are learning about it.

I present case studies of six examples—representing diverse integration approaches and institutional, geographical, and socio-economic contexts—where sustainability was integrated throughout the core curriculum. I analyze these curriculum change approaches with respect to key organizational change dimensions including triggers, change processes, barriers, strategies, and success factors. While not mentioned in any of the case studies, I also highlight successful models of justice, equity, diversity and inclusion (JEDI) within engineering education. Despite massive efforts in recruitment and retention, engineering education is not significantly more diverse than a generation ago. There is growing evidence that engineering focused on sustainability—social sustainability in particular—could help attract and retain females and other historically underrepresented minorities.

While a one-size-fits-all approach for integrating sustainability into engineering education may not work given the uniqueness of different institutions, based on the literature review findings I propose the following recommendations:

1. Leverage Other Reforms, Crises, and Market Positioning to Catalyze Change
2. Adopt an “Integrated” (embedding sustainability into several existing courses) or “Rebuild” (redesigning the entire curriculum) Approach to Incorporating Sustainability
3. Foster Both Top-Down and Bottom-Up Change, with the Department as the Driver
4. Employ “Organizational Development” (where leaders enact top-down policy changes) and “Faculty Learning Communities” (aka “ask-the-teacher”) Strategies
5. Use Project-Based Service-Learning to Enhance Learning, Inclusivity, and Branding

1. INTRODUCTION

The Engineering for One Planet (EOP) initiative is working to transform engineering education to enable all future engineers to be equipped with fundamental principles of environmental and social sustainability. The first implementation tool of this initiative is the Engineering for One Planet (EOP) Framework, which comprises a set of fundamental sustainability learning outcomes (LOs) for all graduating engineers (Engineering for One Planet, 2020). A challenge to this vision is that engineering education is one of the most resistant-to-change areas of higher education (Leydens & Lucena, 2017). This problem is systemic and thus requires a systemic solution (Gilbert, 2018). This report synthesizes key findings from a literature review that focused on identifying systemic barriers, strategies, success factors, and models relevant to integrating the LOs outlined in the EOP Framework throughout engineering education.

The following research questions were used to guide the literature review:

- What systemic changes are needed to embed sustainability into engineering education?
- What are successful curricular and institutional change models?
- What factors were useful for achieving change in particular contexts?
- What are successful models of justice, equity, diversity and inclusion (JEDI)?

2. METHODOLOGY

The literature review process consisted of two phases, shown in Figure 1. In Phase 1 (Search), I conducted exploratory searches using online scholarly reference databases most relevant to engineering education: Scopus, American Society of Engineering Education (ASEE) digital library, Education Resources Information Center (ERIC), ProQuest. I used combinations of relevant keywords, such as: Engineering, Education, Sustainability, Social justice, Curriculum, Transformation. I also conducted known-item searches for relevant authors and organizations.

In Phase 2 (Filtering), I reviewed all resources for inclusion based on three main parameters. The first parameter was *relevance* to the focus on curriculum renewal to incorporate sustainability into engineering education. The second parameter was *impactfulness*, often indicated by a high number of citations. The final parameter was *complementarity* to other resources. Screening steps included 1) read title, 2) read abstract, and 3) skim full text. At the conclusion of the search and assessment process a total of 70 resources were reviewed.

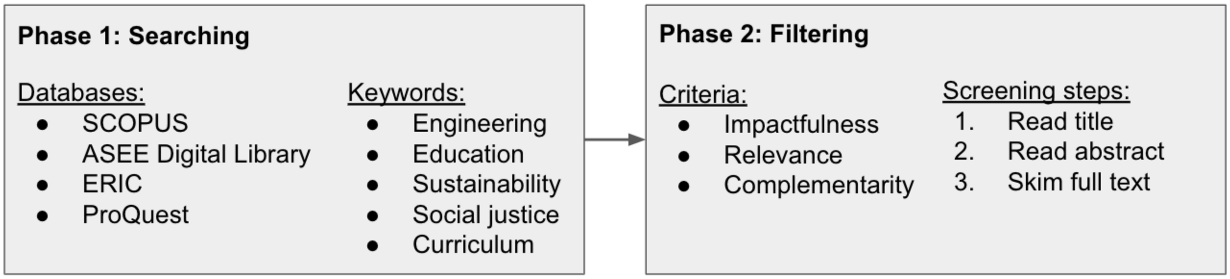


Figure 1. Diagram of literature review methodology.

3. HISTORY OF SUSTAINABILITY IN ENGINEERING

I begin with a brief historical account of the ideologies and institutional factors that have influenced the way engineers engage with sustainability since this provides insight into contemporary challenges and opportunities. This historical account is compiled from various sources (Desha et al., 2009; Froyd et al., 2012; Gutierrez-Bucheli et al., 2022; Hugé et al., 2018; Leydens & Lucena, 2017; Lucena et al., 2010; Mulder, 2004; Mulder et al., 2012; Riley, 2008).

18th and 19th Centuries

The scientifically trained engineer emerged as a product of the Enlightenment, whose main goal was to rationalize and optimize technologies. This sparked a change in educational mode from apprenticeship to teaching of science and math. This change started in France and spread throughout Europe and North America.

1880-1920

Corporations were becoming the main employers of engineers with the emergence of high-volume, low-cost production. This led to further specialization and relevance to industry in the engineering curriculum. Conservative ideology had come to dominate engineering, and engineers rejected the idea of social responsibility.

1930s

The Wickenden Report (1930), commissioned by the Society for the Promotion of Engineering Education (SPEE), now known as the American Society for Engineering Education (ASEE), called for close integration of the scientific, humanistic, and technological elements of engineering. However, no such widespread integration occurred.

1940s-1950s

Engineers were motivated by the ideology of modernization: the belief that it is possible to modernize the world through science and technology by exploiting and controlling nature as a resource and implementing large-scale development projects (e.g., hydroelectric dams) to increase production and consumption. An example is the Green Revolution (1945), which transformed agriculture via high yield crops brought by artificial fertilizers and pesticides. The highly influential Grinter Report (1950), commissioned by the ASEE, argued that engineering science should be the most important body of knowledge in the engineering curriculum.

1960s

After the rise of the Cold War and Sputnik, most engineering education initiatives, including ABET criteria, were aimed at making engineering based more on basic sciences rather than design, in part to gain legitimacy among scientists and science.

1970s

Social and environmental impact emerged as a concern for a few engineering professionals, educators, and students for a variety of historical reasons, including public backlash against use of military technology in the Vietnam War and questionable outcomes of the Green Revolution (e.g., the negative impact of fertilizers and monocultures on ecosystems and local economies).

A few engineering societies and schools organized conferences and created degree programs concerned with social and environmental impacts, such as UC Davis, Stanford, Cornell, SUNY Stony Brook, Penn State, Lehigh, MIT, Virginia Tech, and Rensselaer Institute of Technology. However, they did not become mainstream because tenure and promotion systems that reward siloed disciplinary scholarship led faculty to shy away from further and wider collaborations and integrations.

1980s

The 1980s saw the rise of neoliberal economics, which focused engineers on enhancing the economic competitiveness of the U.S. The United Nations (U.N.) Brundtland Report (1987), also called “Our Common Future,” launched the concept of sustainable development on a global scale.

1990s

The 1992 U.N. conference on environment and development (aka the Rio Earth Summit) was a response to the failures of the development strategies of the 1970s and 1980s. At this conference, 179 governments met to discuss the role of different industries toward sustainable development. This meeting resulted in the Rio Declaration on Environment and Development.

Following these international calls for change in the late 1980s and early 1990s, a small number of engineering education institutions undertook curriculum renewal toward sustainability: Delft University of Technology, Chalmers University of Technology, and UPC Spain. Various engineering organizations hosted conferences, revised codes of ethics, and challenged members to address sustainable development in their work.

In 1997, following nearly a decade of development, ABET adopted Engineering Criteria 2000 (EC2000). Pre-1990 ABET had rigid criteria focused on content that many engineering deans and ABET Industry Advisory Council members argued created a barrier to innovation in engineering education. Based on educational research on student objectives and outcomes, the Engineering Accreditation Commission (EAC) of ABET developed a new method that focused on assessment of student learning outcomes rather than content. Initially, most professors strongly resisted this change, but many eventually acquiesced after realizing that direct instructor assessment for student outcomes, which satisfies ABET, can take little additional time for the technical criteria. EC2000 also added environmental, social, ethical, and sustainability constraints and removed the half-year floor and one-year ceiling for humanities and social sciences courses. The criteria are characterized by brevity and open-endedness, which permits interpretation and flexibility. Only 4 of the 11 program outcomes are purely or primarily technical, while the remaining ones all have significant nontechnical emphases.

Two definitions of sustainability emerged during this period: “weak” and “strong”. Weak sustainability, which was adopted by most engineers, does not differentiate between natural and human-made resources, values nature only as a resource, and holds the belief that technology alone will solve environmental problems. Strong sustainability believes natural resources have intrinsic value and cannot be treated like man-made resources due to irreversibility of ecological damage. A handful of engineering educators proposed curricula in sustainable development that were presented at the IEEE International Symposium on Technology and Society (IEEE, 1991), but it did not become a major theme in engineering education.

2000s

In the 2000s there was an explosion of engineering for sustainability due to the historical convergence of key events: globalization of US engineering education, transformation of long term corporate loyalty of engineers, and unparalleled media coverage of social and environmental problems. The first Engineering Education in Sustainable Development conference took place in 2002 (repeated bi-annually) at Delft University of Technology (TU Delft). It focused on educating engineers to understand the relationship between technology and society. The conference helped create collaborations among universities in different countries.

The National Academy of Engineering (NAE) *Engineer of 2020* report (2004) emphasized sustainability. The Barcelona Declaration (2004) made important conceptualizations of engineering education for sustainable development in Europe. This decade also saw the growth of sustainability-focused engineering student organizations, such as Engineers Without Borders (EWB) and Engineers for a Sustainable World (ESW).

2010s

Changes in the institutional landscape supported greater focus on sustainability, such as grant money from the National Science Foundation (NSF) for projects seeking to integrate sustainability. Yet despite these commitments and increasing incorporation of sustainability into engineering schools, sustainability is not yet a guiding principle and there is little evidence that most engineering students are learning about it.

4. OVERVIEW OF SUSTAINABILITY INTEGRATION IN ENGINEERING EDUCATION

There has been a rapid increase in the number of engineering schools that have incorporated sustainability in the last two decades (Thürer et al., 2018). For example, a U.S. national survey of more than 400 engineering faculty and department heads in 2007 and 2008 revealed that 80% of institutions offered sustainability-related courses and 23% reported BS or MS programs (Davidson et al., 2010; Murphy et al., 2009). I provide an overview of various implementation efforts in terms of global region, engineering discipline, stakeholders, content and pedagogies, location in the curriculum, integration approach, and metrics of success.

4.1 Global Region

The global regional distribution of sustainable engineering courses and modules identified in prior literature reviews (based on 167 articles published between 1993 and 2021) is shown in Figure 2 (Gutierrez-Bucheli et al., 2022; Mesa et al., 2017; Thürer et al., 2018). The universities that were explicitly identified are listed in the Appendix. A few regions—Australia, Europe, and North America—have had the most sustainability implementations due to national initiatives promoted by professional associations and accreditation bodies.

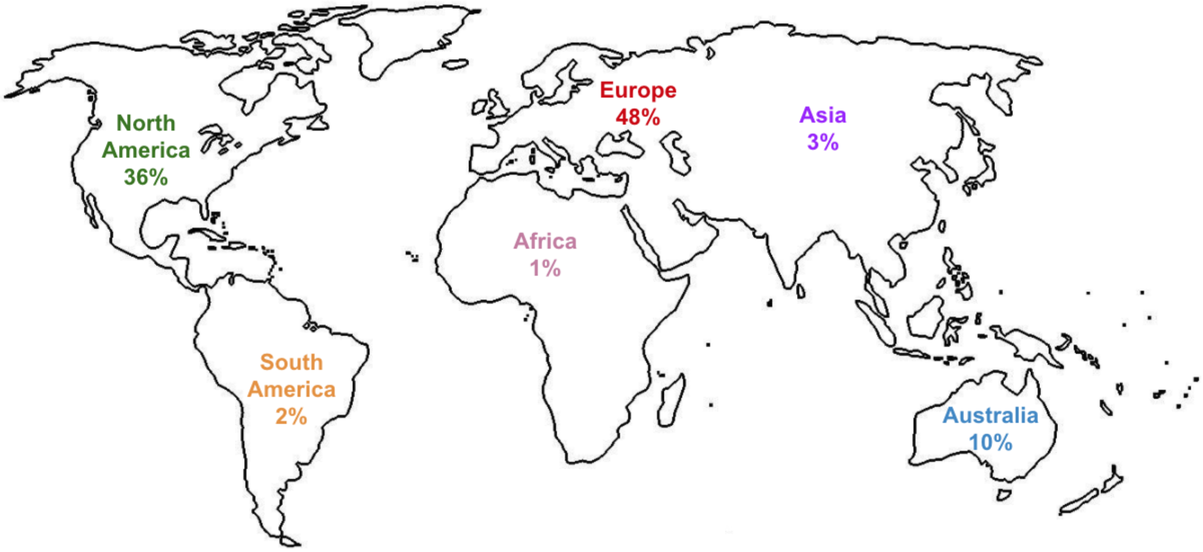


Figure 2. Regional distribution of 167 implementation case studies from prior literature reviews.

4.2 Engineering Discipline

Two questionnaires in 2008 and 2009 identified 155 sustainability courses and modules in the U.S., and two literature reviews in 2017 and 2018 identified an additional 109 courses and modules across the globe (Davidson et al., 2010; Mesa et al., 2017; Thürer et al., 2018). The distribution of these modules and courses by engineering field is presented in Figure 3. Civil and environmental engineering had the highest number of modules and courses, possibly because sustainability largely grew out of initiatives to address environmental concerns that historically have been the purview of this discipline. General engineering—courses often designed as common requirements for all engineering programs—is the category with the second highest number of sustainability modules and courses.

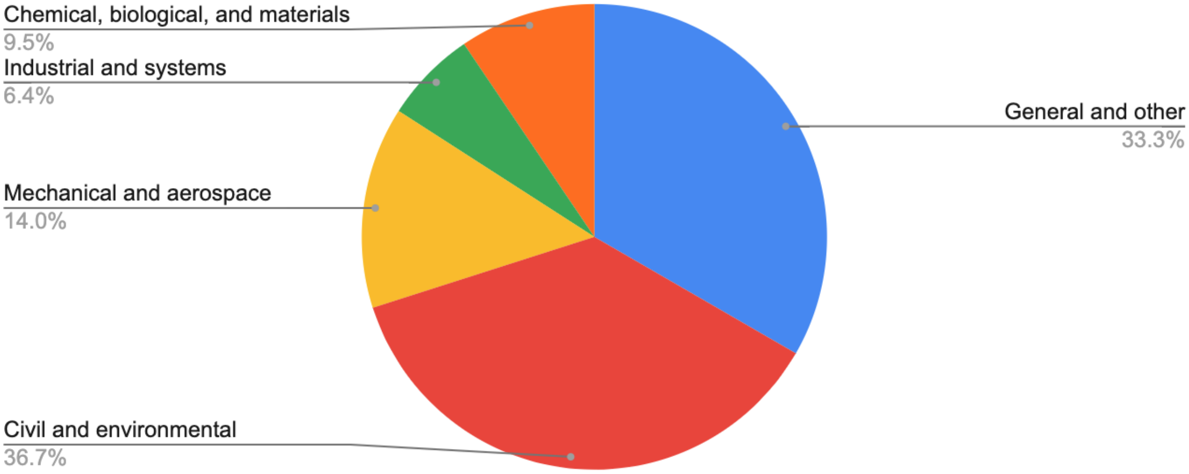


Figure 3. Disciplinary distribution of 264 modules and courses from prior studies and reviews.

4.3 Stakeholders

I briefly describe some of the key engineering education stakeholders, including their power to influence the system and their interest in sustainability.

Accreditation Bodies

The primary accreditation body in the U.S. is ABET, which is charged with quality assurance for engineering programs (Froyd et al., 2012). ABET requirements for program outcomes and assessment identify knowledge, skills, and behaviors students should possess when they graduate (Huntzinger et al., 2007). These ABET criteria are the product of a slow, lengthy, political, and bureaucratic process (Gilbert, 2018; Huntzinger et al., 2007). ABET 2000 included some sustainability criteria for the first time (Leydens & Lucena, 2018).

Administrators

Department and university administrators have official power to sanction institutional change. Small numbers of higher education administrators, particularly department heads, have led efforts to implement new sustainability programs (Thürer et al., 2018).

Corporations

Corporations are important stakeholders not only as future employers of engineers but also as holders of resources needed to make large-scale changes for sustainable production and consumption (Rao et al., 2013). Corporations have lobbying power with accreditation bodies and universities as an interest group (Huntzinger et al., 2007). Industry supports production of engineers by supplying funding to universities for capstone projects, but these are generally limited to a duration of one year (usually senior) and emphasize traditional engineering (Huntzinger et al., 2007).

Technology-intensive firms, especially AT&T and its Bell Labs, were critical early supporters of sustainability (Allenby et al., 2009). However, some scholars have raised concerns about the actual level of commitment within industry. For example, Ford indicates it is a leader in environmental responsibility, but its Health and Environmental Policy reveals a contradiction where practicality will trump sustainability in some cases (Huntzinger et al., 2007). This also creates a tension in employability: sustainable engineers may be more employable due to changing industry needs towards addressing complex problems in a sustainable manner, yet perhaps less employable since sustainability might oppose the status quo in industry driven by short-term profits (Huntzinger et al., 2007; Rao et al., 2013).

Faculty

Individual engineering faculty members are typically responsible for their own course content, but are also guided by requirements on what learning outcomes they must meet (such as ABET). Faculty have been the primary implementers of sustainability curriculum changes by far (Thürer et al., 2018).

Funding Agencies

The National Science Foundation (NSF) is the main funding source for curriculum development in the U.S. (Leydens & Lucena, 2018). The NSF has recently started to fund some sustainability efforts in engineering education (Leydens & Lucena, 2018). However, some faculty have mentioned difficulties in obtaining NSF funding for sustainability curriculum development and faculty support efforts (Gilbert, 2018).

Professional Associations / Societies

Professional societies sponsor conferences, publish journals, set professional and educational standards, and provide job and career services for their members. There are numerous professional associations in the United States, including:

- American Academy of Environmental Engineers and Scientists (AAEES)
- American Institute of Aeronautics and Astronautics (AIAA)
- American Institute of Chemical Engineers (AIChE)
- American Society of Civil Engineers (ASCE)
- American Society of Mechanical Engineers (ASME)
- Institute of Electrical and Electronics Engineers (IEEE)
- Institute of Industrial and Systems Engineers (IISE)

An exemplary association regarding sustainability is ASCE, which requires its members to use principles of sustainable design whereas other associations do not. To support this requirement, ASCE has created a *Body of Knowledge* that includes a section on sustainability and associated cognitive and affective outcomes, as well as a *Commentary* on the ABET criteria that helps educators make connections to the *Body of Knowledge* (Desha et al., 2019).

Students

There has been increasing engineering student demand for sustainability in the last decade (Bielefeldt, 2011; Leydens & Lucena, 2017). Many programs, departments, and universities are motivated to make curricular changes towards sustainability in order to satisfy this rising student demand (Desha et al., 2009; Hugé et al., 2018).

4.4 Content and Pedagogies

The triple bottom line model (economic, environmental, and social dimensions) is the most prevalent sustainability content in engineering education (Gutierrez-Bucheli et al., 2022; Mesa et al., 2017). The focus in most curricula is on economic sustainability, with some increasing consideration for environmental sustainability (Leydens & Lucena, 2017). Social sustainability has been largely neglected and undervalued in engineering education (Leydens & Lucena, 2017; Thürer et al., 2018).

Different pedagogies and assessment methods are better suited to helping students attain particular cognitive abilities related to sustainability (Bielefeldt, 2013; Huntzinger et al., 2007; Segalàs et al., 2010), as shown in Table 1.

Table 1. Effective teaching and evaluation methods for sustainability.

Cognitive Level	Teaching Methods	Evaluation Methods
1. Knowledge	● Lecture (introduce concepts) ● In-class activity	● Assignment to define sustainability
2. Comprehension	● Readings	● Concept maps
3. Application	● Case studies ● Software tools	● Case study analysis
4. Analysis	● Case studies ● Project-based learning	● Case study analysis ● Project reports ● Presentations ● Journals
5. Synthesis	● Capstone design ● Project-based service-learning	● Project reports ● Presentations ● Journals
6. Evaluation	-	-

Problem- and project-based learning (PBL) is one of the most effective pedagogies for teaching sustainable engineering (Faludi & Gilbert, 2019; Mulder et al., 2012). In PBL, students are presented with complex, ill-defined problems. PBL can foster motivation to learn, initiative, interdisciplinary knowledge, collaboration, problem solving, systemic thinking, creativity, communication, critical thinking, independence, and self-directed learning (Du et al., 2013; Guerra, 2017; Huntzinger et al., 2007). A study of ten sustainability courses from five European technological universities found that those using a PBL approach showed the largest increases in students' knowledge of sustainability (Segalàs et al., 2010). Another study that surveyed 515 students ranging from first year through graduate studies in a variety of engineering majors at three diverse universities found that participation in more experiential, active, service-based learning experiences (such as PBL) correlated to higher sustainability self-efficacy, value, and affect (McCormick et al., 2015). However, PBL can require a lot of effort, resources, and relationships, as it is often done in collaboration with external partners (Mulder et al., 2012).

4.5 Location in the Curriculum

There are various places in the curriculum where sustainability has been incorporated, which are listed in Table 2 along with an assessment of their general suitability. In general, incorporating sustainability into required courses is more difficult than elective courses, but they can reach more students and provide legitimacy for sustainability (Faludi & Gilbert, 2019).

Table 2. Locations in the curriculum where sustainability has been incorporated.

Location	Example	General Assessment
Engineering sciences (ES) courses	Stochastic Models for Civil Engineering course (Sattler et al., 2012)	It is challenging to implement sustainability in ES courses because this is where students come to value and master the narrow, context-free engineering problem solving method (Leydens & Lucena, 2018).
Design courses	Capstone senior design course (Sattler et al., 2012)	Design courses are an ideal venue for sustainability, but they constitute only a small fraction (<15%) of engineering programs and are overburdened with meeting most of the ABET criteria simultaneously (Leydens & Lucena, 2018).
Humanities & social sciences (HSS) courses	Science, Technology, & Society (STS) course (Leydens & Lucena, 2018)	Incorporating sustainability via HSS will place it in a marginalized position not seen as integral to “real” engineering (Leydens & Lucena, 2018).
Technical elective courses	Engineering Projects in Community Service (EPICS) course (Oakes et al., 2018)	The existence of an elective has been used as an argument by faculty to not introduce an obligatory course, although they can be complementary (Mulder et al., 2012)
Co-curricular activities	Internship at a company focused on sustainability (Pearson Weatherton et al., 2012)	Internships have been found to correlate with high sustainability self-efficacy but lower affect (McCormick et al., 2015).
Extra-curricular activities	Student clubs like Engineers Without Borders (Litchfield & Javernick-Will, 2014)	Extra-curricular club involvement has been found to correlate with lower sustainability self-efficacy but high value (McCormick et al., 2015).

4.6 Incorporation Approach

There are three typical approaches to incorporating sustainability into the curriculum (Mesa et al., 2017; Murphy et al., 2009; Thürer et al., 2018), which are listed in Table 3. Most sustainability integration appears to be done in a piece-meal fashion; few institutions have thoroughly embedded sustainability throughout the curricula (Thürer et al., 2018).

Table 3. Common approaches for incorporating sustainability into engineering curricula.

Approach	Description	Frequency
Vertical / Add-on	Create a new, stand-alone course	By far the most common
Horizontal / Integrated	Embed into several existing courses	Somewhat common
Rebuild / Redesign	Create a new program	Rare

Embedding sustainability broadly within regular courses (horizontal integration) may be better than vertical integration for reaching more students (Faludi & Gilbert, 2019) and for encouraging students to view sustainability in a systemic and holistic manner (Watson et al., 2013). One study compared the conceptual sustainability knowledge of students at two institutions that differ in their approaches of integrating sustainability into curricula (one vertical, the other horizontal) and found that horizontal integration leads to broader, deeper, and more connected knowledge (Barrella & Watson, 2016). Another study compared student projects in two stand-alone sustainable engineering courses (85 projects) and two senior design courses (43 projects) and found that the stand-alone projects exhibited higher levels of cognition, increased linkage of the three pillars of sustainability, and greater breadth of sustainability topics (Ketchman et al., 2017). The authors suggest that senior design courses have the potential to stockpile many ABET outcomes, potentially leading to dilution of the outcomes.

4.7 Indicators and Metrics of Success

Various indicators of successful educational systems change toward sustainability have been proposed (Staniškis & Katiliūtė, 2016), and are listed in Table 4.

Table 4. Indicators of successful educational systems change toward sustainability.

Strategy of the university / program	● Is there a well-defined sustainability strategy integral to institutional identity and values?
Education and curriculum	● Are learning objectives defined in curricular and student assessments? ● Are learning objectives being met?
Student experience	● Are students involved in sustainability outside the curriculum? ● Are students being placed in jobs related to sustainability?

Commonly used metrics to assess the nature and extent of sustainability learning objectives in curricula include: (1) percentage of courses contributing to sustainability, and (2) breadth and depth of coverage of sustainability issues. A widely used tool to assess these metrics is the Sustainability Tool for Assessing UNiversities' Curricula Holistically (STAUNCH) (Watson et al., 2013). STAUNCH evaluates syllabi against the assessment criteria listed in Table 5.

Table 5. STAUNCH curricula contribution to sustainability assessment criteria.

Economic	Environmental	Social	Cross-Cutting
● GNP/Productivity ● Resource use ● Finances ● Production and consumption patterns ● Development economics ● Markets, commerce, and trade ● Accountability	● Policy / Administration ● Products and services: Life Cycle Assessment (LCA) ● Pollution, toxic waste ● Biodiversity ● Resource efficiency ● Climate change ● Resource uses ● Desertification ● Alternative energy and technology	● Demography ● Employment ● Poverty ● Bribery / corruption ● Equity / justice ● Health ● Politics ● Education & training ● Diversity and social cohesion ● Culture and religion ● Labor / human rights ● Peace and security ● Work-life balance	● People as part of nature ● Limits to growth ● Systems thinking ● Responsibility ● Governance ● Holistic thinking ● Long term thinking ● Communication ● Sustainable development ● Disciplinarity ● Ethics / Philosophy ● Transparency

5. EXEMPLAR INTEGRATED PROGRAM

An example program where sustainability has been integrated throughout the undergraduate curriculum is the University of Texas at Arlington (Pearson Weatherton et al., 2012, 2015; Sattler et al., 2012). The integration effort was led by a faculty team from the Civil, Industrial, and Mechanical Engineering Departments who acquired two-year funding from the NSF for their proposal “Engineering Sustainable Engineers.” Key program elements (shown in Figure 4) include sustainability learning modules, quality sustainability internships, and a multidisciplinary senior design project with a sustainability focus. The expected learning outcomes were: A) increased knowledge of sustainability concepts; B) increased ability to analyze project components for sustainability; C) improved ability to propose mitigation strategies for reducing negative impacts; and D) ability to apply knowledge to real-world problems and projects. Surveys and pre- and post-tests were employed to assess achievement of learning outcomes.

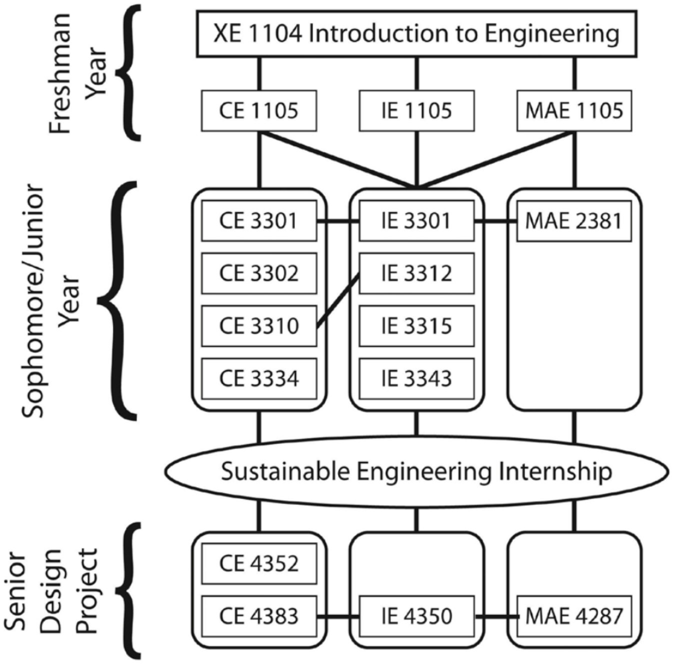


Figure 4. Key elements of the sustainable engineering program at UT Arlington.

5.1 Sustainability Learning Modules

Eleven sustainability modules were developed for integration into 17 traditional engineering courses across all levels of matriculation. Freshman year modules consisted of introductory modules for four required first year courses. These modules allowed new materials to be added without adding more courses and ensured all students would be exposed to sustainability concepts. Most modules were designed to be covered in one class period, and designed to be “grab-and-go” ready for faculty. Each module was designed to assess all three pillars of sustainability, but social aspects were most difficult to quantify. Eight of the modules included some kind of active learning component. There were 3,249 instances of student contact with the modules. Students had low assessment results in the first year, so modules were refined and student outcomes improved, with 75% of students indicating they were confident or strongly confident in their abilities to perform the objectives for each module. For 5 of the 7 modules with test results, the post-test mean score exceeded the pretest mean by less than a 75% level of confidence.

5.2 Sustainable Engineering Internships

The faculty team partnered with local industry to offer quality sustainable internships. To identify companies with exemplary sustainable design and operation practices, the team created a "Quality Sustainable Engineering Internship Survey" that was sent to over 250 companies that hire engineers in the Dallas-Fort Worth area. Six students were placed in paid internships with four companies (Kimley-Horn and Associates, Facility Performance Associates, PepsiCo, and Kroger Manufacturing) over two summers. The nature of the work that the students performed met expectations in terms of the students being involved in actual sustainable engineering design and decision-making. All students indicated the internship helped them attain the learning objectives to a moderate or great extent. All students were more likely to consider sustainability in their careers and agreed they would recommend the internships to others. All companies wanted to participate again and would recommend the program to other companies.

5.3 Multidisciplinary Senior Design Project

Students from all three engineering disciplines collaborated to design a portable biodiesel production facility to refine waste vegetable oil from campus dining facilities to biodiesel for use by the university fleet and generators. On post surveys, 75-100% of respondents (n=4) stated the project increased their ability to achieve outcomes A, C, and D. Only 50% stated that it increased their ability to identify ways to mitigate potential negative impacts of sustainability. 100% of students agreed or strongly agreed that because of the project they will be more likely to consider sustainable design options in their future careers.

5.4 Challenges

One challenge was buy-in from instructors who were not part of the core faculty team leading the integration effort. A second challenge was the aggressive timeline, as NSF funding only provided 2 years to develop, implement, and assess the entire program. These two challenges led to a third challenge regarding assessment, which was the small sample sizes.

6. CASE STUDIES OF SUCCESSFUL CURRICULAR CHANGE

Each of the three sustainability integration approaches (vertical, horizontal, rebuild) requires distinct strategies for changing the curriculum and culture (Kolmos et al., 2016). Here, I present case studies of examples where sustainability was integrated throughout the core curriculum (not a mere add-on). Case studies can reveal the multiplicity of factors that have interacted to produce the unique character of the entity under study. The cases, listed in Table 6, represent diverse institutional, geographical, and socio-economic contexts as well as diverse integration approaches. After briefly describing the context for each case, I analyze the curriculum change approaches with respect to key organizational change dimensions including triggers, change processes, barriers, strategies, and success factors (Hugé et al., 2018).

Table 6. Case study details.

Institution	Country	Integration Approach	References
Chalmers University of Technology	Sweden	Integrated	(Holmberg et al., 2008; Svanström et al., 2012)
Delft University of Technology	The Netherlands	Add-on & Integrated	(Holmberg et al., 2008; Kamp, 2006; Mulder, 2004, 2006; Peet et al., 2004)
Georgia Institute of Technology	United States	Rebuild	(Meyer & Jacobs, 2000; Watson et al., 2013)
Tecnológico de Monterrey	Mexico	Rebuild	(Lozano & Lozano, 2014)
University of Cambridge	England	Add-on & Integrated	(Fenner et al., 2005)
University of Technology, Sydney	Australia	Rebuild	(Bryce et al., 2004)

6.1 Case Contexts

I briefly describe the relevant context of each institution and its curriculum change effort.

Chalmers University of Technology

Chalmers, established in 1829, is a private technical university with 10,000 students. Environmental research and education at Chalmers goes back all the way to the 1970s. The main responsibility for courses lies not with departments but a central university organization, which facilitates cooperation within and between programs and makes it easier to implement top-down demands. The case study focuses on a 3-year (2006-2009) reform project to achieve greater integration of sustainability in engineering programs. Courses on sustainability are now given by many different groups at many different departments.

Delft University of Technology (TU Delft)

TU Delft is a public university that was established in 1842. With 13,000 students, it is the largest technical university in The Netherlands. TU Delft has a history of research and education related to environmental impacts of technology dating back to the 1980's. Faculty are responsible for the content of courses, while educational directors coordinate and tune the different courses to each other. The case study focuses on a multi-year effort in the 1990's and 2000's to integrate sustainability into the curriculum via three components: an elementary course "Technology in Sustainable Development" for all students, intertwining of sustainability into all regular disciplinary courses, and a specialization in sustainability.

Georgia Institute of Technology

Georgia Tech is a public university that was founded in 1885 and has more than 21,500 students. The case study focuses on the School of Civil and Environmental Engineering (CEE). With almost 800 undergraduates, the school is one of the largest academic CEE programs in the US. The case describes a curriculum reform effort in the late 1990's that emphasized sustainability as one of the key elements.

Tecnológico de Monterrey

Tecnológico de Monterrey is a private university that was established in 1943. It evolved into a multi-campus system of 31 campuses in major cities throughout Mexico. The main campus in Monterrey has ~16,500 students. The case study focuses on an initiative in the late 2000's to create a new bachelor's degree focusing on engineering in sustainable development.

University of Cambridge

Cambridge, founded in 1209, is a public university with 12,850 undergraduates. The case study focuses on the Department of Engineering, which has over 1,100 students. The department offers degrees in engineering science so graduating students are regarded as broadly based, which provides a basis for embracing multi-disciplinary approaches. The management of the department is by consensus, making decision making and incisiveness challenging. Many individuals were already advocating sustainable development concepts prior to the work described here. The case study focuses on a 5-year process of integrating sustainability into the department in the early 2000's.

University of Technology, Sydney (UTS)

UTS is a public university. It was founded in 1988, but its origins can be traced to the 1870s. It enrolls over 40,000 students. The case study focuses on the engineering school. Facing several threats and opportunities in the late 1990s, a common agenda emerged among the engineering faculty: develop a single undergraduate program underpinned by sustainability and taken by all prospective engineers. The curriculum included an "Engineering for sustainability" course designed to be taken by all students as well as a group of other courses designed to embed sustainability throughout the undergraduate experience.

6.2 Triggers

Factors that triggered the change process in each case, both internal and external to the institution, are listed in Table 7. These triggers are unique and vary across the cases, but some cross-cutting themes can be identified. Most cases involved internal recognition of the importance of sustainability (e.g., by department or university leaders). Most cases also involved some sort of external trigger related to either national policies and laws, accreditation, or funding. Other case studies of systemic change in engineering education have similarly found that the process is often triggered by a "crisis" (e.g., accreditation, funding, enrollment) (Graham, 2012).

Another insight is the potential for using external reforms as an opportunity for other changes, as in the Georgia Tech case. One such reform initiative in Europe is the Bologna process, which specifies several requirements for higher education curricula. One requirement is that faculty must redesign their course syllabus descriptions to contain explicitly formulated learning outcomes in terms of knowledge, skills, and competencies (Kolmos et al., 2016). Another requirement is that departments must offer separate but linked bachelor's and master's degrees (Holmberg et al., 2008).

Table 7. Triggers that catalyzed the change process in each case.

Institution	Internal Triggers	External Triggers
Chalmers University of Technology	2003: President decides that all students must take the equivalent of a five week course in environment and sustainable development 2008: Chalmers vision statement: “Chalmers for a sustainable future”	2006: Swedish law states that all university activities should promote sustainability 2006: Swedish National Agency for Higher Education (accreditation agency) criticized the engineering programs for not fulfilling part of the degree ordinance related to sustainability 2006: Chalmers received a UNESCO chair in sustainability and approved a 3-year reform project on sustainability education
Delft University of Technology	1991: TU Delft adopted an environmental policy stating that guidelines for introducing sustainable development into engineering curricula had to be formulated within 3 years 1994: The University Council adopted a new strategic vision: “Towards a new commitment,” which emphasized the importance of sustainable development	1990: National Environmental Policy Plan of the Netherlands 1994: Universities and professional associations convinced the Dutch government to extend undergrad training from 4 to 5 years to ease pressure on students and reduce the soaring dropout rate of engineering schools
Georgia Institute of Technology	1995: the Board of Regents of the University System of Georgia voted to switch from a quarter- to a semester-basis and asked academic units to take advantage of this opportunity to incorporate new curriculum	1997: New ABET 2000 criteria allude to sustainability
Tecnológico de Monterrey	2009: The campus president decided that a new bachelor’s degree in engineering for sustainable development was needed to provide professionals versed in sustainability	
University of Cambridge	Existing faculty interest in sustainability (e.g., in the Manufacturing Division)	1999: Royal Academy of Engineering (RAE) funded a Visiting Professor in Engineering Design for Sustainable Development 2000: RAE funded a UK Chair in Engineering for Sustainable Development with the goal of making sustainable development central to engineering education
University of Technology, Sydney	1996: The University, recognizing sustainability as an area with important corporate and academic opportunities, enacted a strategic “sustainability policy,” which stipulated that curricula, teaching, research, community service, and institutional practices must emphasize achievement of sustainable futures	1996: Widespread public sector economic restructuring put faculty under severe financial pressure 1996: Following a national review of engineering education, the Institution of Engineers Australia (IEAust) recognized sustainability in its code of ethics

6.3 Change Processes

Curriculum renewal in engineering education can involve top-down and/or bottom-up processes (Desha et al., 2009; Fenner et al., 2005; Hugé et al., 2018; Kolmos et al., 2016). In top-down processes, administrators initiate change to integrate new content across program offerings and most staff are involved. In bottom-up (or ad hoc) processes, individual faculty (early adopters) carry out changes within single and isolated courses, build support, and sometimes eventually gain formalization. The change process for each case is defined and described in Table 8.

Table 8. Curriculum renewal process for each case.

Institution	Type	Description
Chalmers University of Technology	Top-down	● A special "resource group" of experienced sustainability education faculty from many disciplines was given the task of approaching faculty and program directors with the aim of embedding sustainability over a 3-year period, although complete integration was not fully achieved
Delft University of Technology	Top-down	● A committee was installed by the University Board to draw up plans to integrate sustainability into the curriculum over a 3-year period, and implementation was funded over a 7-year period
Georgia Institute of Technology	Top-down	● The University Board asked that academic units take advantage of a change in academic year basis to incorporate new courses and content ● The Department of Civil and Environmental Engineering completed the curriculum development process in 1 year
Tecnológico de Monterrey	Top-down	● A faculty committee was appointed to design the curriculum ● The iterative process took 2 years
University of Cambridge	Bottom-up	● A single faculty member began teaching a course in engineering design for sustainable development, with positive student feedback ● A group of faculty established the Centre for Sustainable Development and began delivering other courses and modules throughout the curriculum ● Several open meetings with faculty across the department to embed sustainable development into all stages and topics of the engineering department ● The process evolved over 5-years and integration had not been reached
University of Technology, Sydney	Top-down	● A common agenda emerged among the faculty ● The dean set up a working party to explore the new program ● Momentum developed through alliance of management (concerned with finances) and staff (concerned with teaching relevance) ● Planning directors were appointed to develop program planning on the basis of a "sustainability" theme ● The process took 2 years

The findings suggest that the type of sustainability incorporation approach (add-on, integrated, rebuild) and change process (top-down, bottom-up) can significantly affect the curriculum renewal duration. The three cases using a curriculum rebuild approach, which is inherently top-down, all completed the process in 1-2 years. Chalmers used a top-down, integrated integration approach that took 3 years. Delft employed a top-down add-on and integrated approach, which took 10 years. The bottom-up process at Cambridge, which began as an add-on approach and evolved into an integrated approach, had yet to achieve full integration after 5 years. Another case study of sustainability integration in engineering education that examined six universities across five countries also found that bottom-up processes took longer than top-down approaches (Hugé et al., 2018).

In all cases except one, the change process began as part of a top-down, department-wide plan and tended to be more holistic. A bottom-up approach places the onus on individual faculty champions who typically have little or no support from their institution, which seldom results in systemic change (Faludi & Gilbert, 2019; Graham, 2012; Kolmos et al., 2016). A large study by the Royal Academy of Engineering that sought to identify general features of successful reform in engineering education discovered that the chances of success are maximized when efforts are led by entire departments (Graham, 2012). This is in contrast to the current situation, in which most sustainability implementations are done by individual faculty (Thürer et al., 2018).

However, solely utilizing a top-down approach seems to be insufficient. All of the top-down cases required buy-in from most faculty, and the bottom-up case had at least some formal recognition and support from the administration and other key academic leaders. Some engineering education researchers have argued that bottom-up and top-down initiatives are strongly coupled and co-evolving (Mulder et al., 2012), and that both approaches are needed to realize widespread cultural change (Faludi & Gilbert, 2019; Kolmos et al., 2016). A case study of a successful faculty-wide engineering curriculum transformation at University College London involved both top-down and bottom-up processes: leadership defined the high-level vision and drove the educational change program while providing space for faculty to take ownership within the prescribed boundaries (Mitchell et al., 2021).

The following steps, which have been identified in other studies of curriculum renewal (Desha et al., 2009), were used in many of the top-down curriculum change processes:

- Step 1: Bring staff to a common understanding of the challenges and opportunities for curriculum renewal
- Step 2: Establish a faculty committee or working group, often composed of existing change leaders/champions, to plan the new curriculum
- Step 3: Systematically review sustainability in existing courses and identify areas of focus for introduction and consolidation of content
- Step 4: Iteratively seek feedback from other faculty, students, industry, and government
- Step 5: Operationalize the curriculum

6.4 Barriers

Barriers to integrating sustainability into engineering education that were identified in the six cases are listed in Table 9. Similar barriers have been identified in other relevant literature (Ashford, 2004; Boyle, 2004; Faludi & Gilbert, 2019; Gilbert, 2018; Huntzinger et al., 2007; Leydens & Lucena, 2017; Mulder et al., 2012; Riley, 2008; Zhang et al., 2012). Several mindsets and ideologies deeply embedded in engineering culture render sustainability marginal or irrelevant (Karin et al., 2015; Karwat et al., 2015; Lucena et al., 2010; Rao et al., 2013; Riley, 2008), which are listed in Table 10.

Table 9. Barriers to integration of sustainability identified in the case studies.

Engineering Culture	● Sustainability often considered a vague “soft” skill that lies outside of engineering ● Emphasis on that which can be quantified
Academic Culture	● Siloed nature of disciplines: sustainability requires a multi- and trans-disciplinary approach that lies outside of traditional disciplinary boundaries ● Lack of incentives: integrating sustainability into engineering does not complement the rewards and recognition systems in place at most educational institutions ● Many faculty highly value academic freedom and the need to teach disciplinary skills
Organizational Culture	● Sharp divides between departments: various courses are “owned” by separate units ● Funding: changes in curricula impose financial costs and departmental discussions on reform can spark internal conflict regarding division of assets ● Anything new that draws resources and energy from traditional programs may potentially hurt rankings and will be disfavored
Societal Culture	● Industry needs and priorities ● National values ● Mainstream political ideologies
Curriculum	● Engineering curricula are rigidly packed with required technical courses ● Emphasis on predefined, decontextualized, closed-ended problem solving
Faculty attitudes and capacities	● Lack of familiarity with, and preparation to teach, sustainability ● Perceived threats to the integrity and ownership of subject material at the individual course content level ● Must balance the need to meet both technical and sustainability dimensions
Student attitudes	● Students may resist dramatic curricular and pedagogical changes ● Sustainable engineers may be less employable since sustainability might oppose the status quo in industry driven by short-term profit

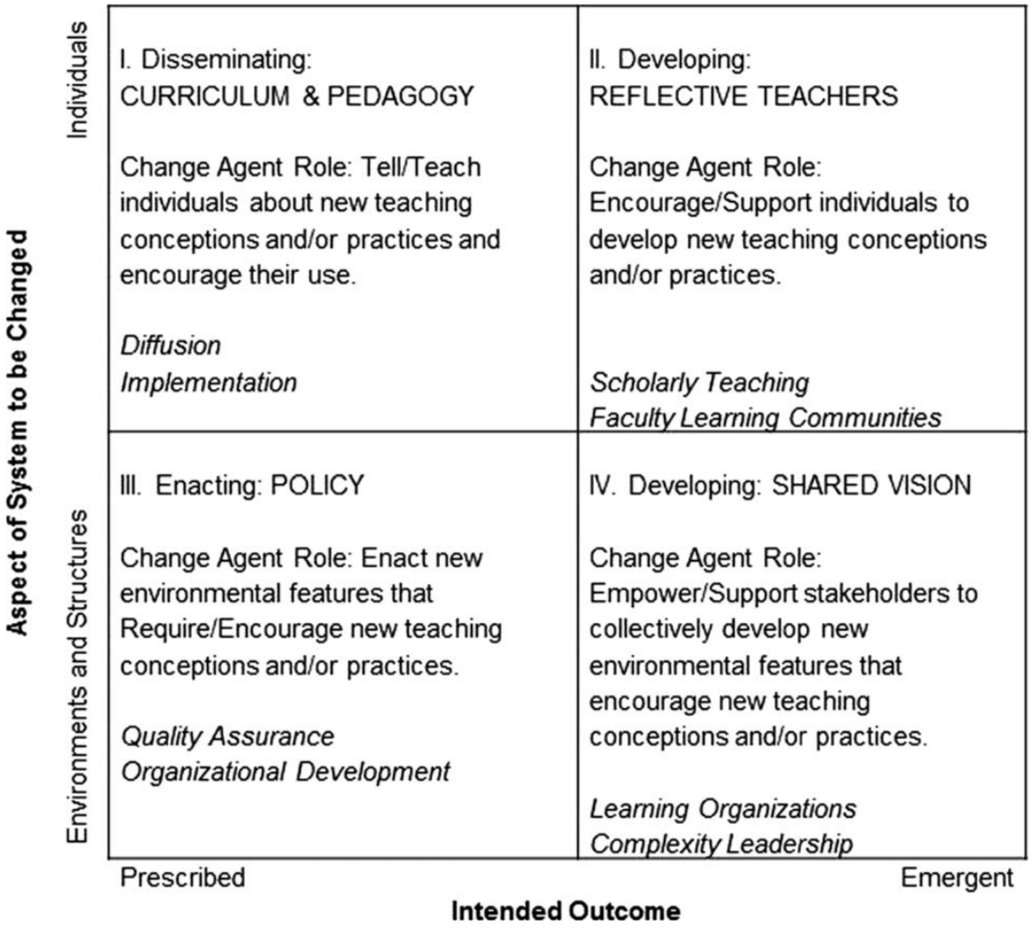
Table 10. Engineering mindsets and ideologies that marginalize sustainability.

Positivism and objectivity	Reliance on the scientific method as the primary (or only) way of knowing about the world
Reductionism	Notion that phenomena and problems can be broken down into smaller components of analysis and that this can fully explain the system as a whole
Technical-social dualism	Belief that the social and the technical dimensions of a problem are separate, and that the social as irrelevant
Techno-solutionism	Belief that technology can unilaterally solve complex social and environmental problems
Consumerism / materialism	Belief that progress means infinite economic and material growth through increasing technological development and resource utilization

6.5 Strategies

Prior work on systemic change strategies in engineering education has categorized strategies using the “Four Categories of Change Strategies” model (Besterfield-Sacre et al., 2014; Borrego & Henderson, 2014; Kolmos et al., 2016), shown in Figure 5. This model has a two-axis grid framework. One axis is the aspect of the system to be changed: individual or environments & structures. The other axis is the intended outcome: prescribed or emergent.

Changing individuals involves change of individual opinions, attitudes, and cognition (Du et al., 2013). Changing environments and structures involves change of management, organizational ethos, disciplines and departmental structures, curriculum contents, and relationships (Du et al., 2013). The Four Categories of Change Strategies model has four categories that can each encompass a variety of change strategies: disseminating curriculum and pedagogy, developing reflective teachers, enacting policy, and developing shared vision. Eight systemic change strategies (two per category) that are often used in engineering education are described in Table 11. The strategies employed in each case are listed in Table 12.



	Prescribed	Emergent
Individuals	I. Disseminating: CURRICULUM & PEDAGOGY Change Agent Role: Tell/Teach individuals about new teaching conceptions and/or practices and encourage their use. *Diffusion* *Implementation*	II. Developing: REFLECTIVE TEACHERS Change Agent Role: Encourage/Support individuals to develop new teaching conceptions and/or practices. *Scholarly Teaching* *Faculty Learning Communities*
Environments and Structures	III. Enacting: POLICY Change Agent Role: Enact new environmental features that Require/Encourage new teaching conceptions and/or practices. *Quality Assurance* *Organizational Development*	IV. Developing: SHARED VISION Change Agent Role: Empower/Support stakeholders to collectively develop new environmental features that encourage new teaching conceptions and/or practices. *Learning Organizations* *Complexity Leadership*

Figure 5. Four Categories of Change Strategies model (Borrego & Henderson, 2014).

Table 11. Descriptions of eight common systemic change strategies in engineering education.

Strategy	Summary	Change Agent Role	Change Mechanism	Metrics of Success
Diffusion	Innovations are created in one location, adopted or adapted by others	Develop a quality innovation and spread the word	Adoption decisions by potential users	Number of users or amount of influence of the innovation
Implementation	Purposeful activities are designed to put proven innovations into practice in a new setting	Develop a training program	Training of potential users	Fidelity of use of innovation
Scholarly Teaching	Individual faculty reflect on their teaching in an effort to improve	Encourage faculty to reflect on their teaching	Evidence-based reflection on practice	Self-reported changes in beliefs, attitudes, practices
Faculty Learning Communities	A group of faculty supports each other in improving teaching	Bring faculty together and scaffold the community	Peer support and accountability	Self-reported changes in beliefs, attitudes, practices
Quality Assurance	Measurable target outcomes are identified and progress is tracked	Develop measurable outcomes and collect evidence	Pressure to meet outcomes	Degree to which outcome measures are met
Organizational Development	Leader develops a new vision and strategy for aligning employee attitudes and behaviors	Develop a new vision and identity strategy for creating alignment	Communicate vision and develop structures to motivate employees	Productivity-related metrics (graduation rates, etc.
Learning Organizations	Leader works to develop an organizational culture that supports knowledge creation	Invest in developing employees' personal mastery, shared vision, team learning	Team-level questioning and revision of mental models	Vague and situation dependent
Complexity Leadership	Create organizational conditions that increase likelihood of productive change	Disrupt existing patterns, encourage novelty, and act as sense makers	Formal leaders encourage new ideas by creating disequilibrium	Vague and situation dependent

The initial strategy used by Chalmers was "diffusion," but this failed because many faculty without a pre-existing interest in sustainability lacked motivation to make changes to their courses. The "diffusion" strategy is one of the most widely assumed strategies in engineering education (Graham, 2012). However, prior studies have found that faculty awareness is rarely sufficient for adoption, which involves considerations such as financial resources, faculty beliefs about value (including costs) and their ability to be successful, faculty attitudes towards sustainability, and complexity of the innovation (Borrego et al., 2010; Brown et al., 2015; Finelli et al., 2014; Matusovich et al., 2014). Case studies of curriculum change in engineering education have found that reform rarely occurred through diffusion, as successful change typically involves approaches developed in-house to suit institutional contexts (Graham, 2012; Mitchell et al., 2021).

At Delft and Cambridge, the "implementation" (aka "teach-the-teacher") strategy faced resistance from faculty because it infringed on their sense of autonomy. Chalmers, Delft, and

Cambridge eventually found success with a “faculty learning communities” strategy known as the “Individual Interaction Method” (aka “ask-the-teacher”). In this strategy, faculty were invited to suggest how their own (sub-)discipline might contribute to sustainability, which sparked their interest and led them to adapt their courses. This keeps ownership with faculty. This method was successful even for faculty not already motivated to make changes toward sustainability. Another case study of engineering curriculum reform found that the ability to draw on existing local experience and expertise was vital to gain buy-in and acceptance (Mitchell et al., 2021).

The “organizational development” strategy was successfully employed by Georgia Tech, Tecnologico de Monterrey, and UTS. Policies included imperatives to integrate sustainability by a certain deadline, and structures included faculty working groups. However, this strategy was insufficient to enact widespread change at TU Delft. This suggests that institutional mandates may sometimes need to be accompanied by individual change strategies (Kolmos et al., 2016).

Table 12. Systemic change strategies employed by each institution.

Institution	Strategies
Chalmers University of Technology	● Diffusion: this strategy failed because faculty without a pre-existing interest in sustainability were not motivated to adopt changes ● Faculty Learning Communities: found success with the “Individual Interaction Method”
Delft University of Technology	● Organizational Development: adopted an environmental policy plan that required sustainability to be integrated into engineering curricula, but this was insufficient ● Implementation: this strategy failed because efforts to train lecturers about sustainability often triggered resistance as they feared loss of autonomy ● Faculty Learning Communities: found success with the “Individual Interaction Method”
Georgia Institute of Technology	● Organizational Development: the Board asked programs to change curricula and the department engaged in a strategic visioning process
Tecnológico de Monterrey	● Organizational Development: the campus president decided a new degree was needed and appointed a committee to design the course content and degree structure ● Implementation: developed a course to educate the educators
University of Cambridge	● Implementation: this strategy failed because efforts to train lecturers about sustainability often triggered resistance as they feared loss of autonomy ● Faculty Learning Communities: found success with the “Individual Interaction Method”
University of Technology, Sydney	● Organizational Development: The dean mapped out a new faculty structure for a single engineering undergraduate program and set up a working party to explore it

Which strategy to use depends on the particular context, including type and specificity of change desired, available resources, and power and position of the change agent (Borrego & Henderson, 2014). Policy change is likely a better choice for a specific change, such as a new curriculum. Use of multiple change strategies may increase the likelihood of success.

6.6 Success Factors

Common success factors across the cases are listed below. Many of these align with findings from other studies of successful systemic curriculum renewal initiatives in engineering education (Desha et al., 2009; Graham, 2012; Hugé et al., 2018; Kolmos et al., 2016; Wormley, 2004).

- Well-articulated vision and goals
- A group of highly motivated and proactive change agents
- Institutional commitment from departmental and university leadership
- Financial resources to support the effort
- Strong personal and/or formal linkages between students, faculty, staff, and administrators to support continuous communication and interaction
- Structural agreements (e.g., policies) that embed sustainability in the university agenda
- A centrally-endorsed center or office in charge of sustainability change processes

7. SUSTAINABILITY AND JUSTICE, EQUITY, DIVERSITY, & INCLUSION (JEDI)

Despite massive efforts in recruitment and retention, engineering education is not significantly more diverse than a generation ago (Leydens & Lucena, 2017). Women and other historically under-represented minorities (URMs) face an “in/visibility paradox”: gender and race are often highly visible, yet they are invisible as engineers (Corple et al., 2018). For example, cultural gender socialization often steers women away from engineering-type activities (Matusovich et al., 2013). Since engineering is largely a masculine culture, women must alter the feminine aspects of their identities to fit in (Corple et al., 2018). While JEDI was not explicitly mentioned in any of the example case studies, sustainability is a promising way to support JEDI efforts.

7.1 Sustainability and JEDI

There is growing evidence that engineering focused on sustainability, and social sustainability especially, could help attract and retain females and URMs. In a study of 316 students (79 women, 35 URMs) in a freshman engineering course at UC Berkeley, a module focused on sustainable human-centered design had the highest proportion of female and URM enrollment compared to traditional engineering modules (Oehlberg et al., 2010). Another study, based on a nationally representative survey of college students in introductory English classes (6,772 responses), found that students hoping to address sustainability-related outcome expectations with obvious human relevance are less likely to pursue engineering, yet those students who perceive “improving quality of life” and “saving lives” as associated with engineering are more likely to pursue the profession (Klotz et al., 2014). A related study using two national surveys (7,451 participants) found that civil engineering students do not identify with wanting to save lives, yet female students interested in civil engineering hope to address poverty and opportunities for women and minorities (Shealy et al., 2016). In a study of 515 engineering students from three universities in the U.S., females reported higher sustainability value and motivation than males (McCormick et al., 2015). Community-engaged learning (also known as service-learning) in particular has been described as an ideal vehicle for both sustainability and inclusiveness in engineering (Bielefeldt & Pearce, 2012; Leydens & Lucena, 2017).

7.2 Community-Engaged Learning (CEL) / Service-Learning (SL)

Community-engaged learning (CEL) and service-learning (SL) activities involve working with a community partner to address a societal issue and critically reflecting on one's learning. There are many reasons why CEL/SL might be more attractive to groups traditionally underrepresented in engineering. For example, instructional strategies using holistic, real-world applications of science and technology tend to be more effective for attracting and retaining women and URMs (Swan et al., 2014). CEL/SL also contextualizes engineering and shows how engineering benefits communities (Bielefeldt & Pearce, 2012; Swan et al., 2014). Furthermore, CEL/SL contexts have the opportunity to provide an environment that challenges traditional engineering cultures, values, and identities with its focus on societal impact and integration of human-centered design processes (Corple et al., 2018).

One example is the Service-Learning Integrated throughout a College of Engineering (SLICE) program at the University of Massachusetts, Lowell (Duffy et al., 2009). After introducing SLICE, Hispanic student enrollment increased 50%. Females and underrepresented racial groups who participated in SLICE indicated a significantly (5%) more positive impact on retention on average. Two other well-known, optional CEL/SL activities in engineering that have significant over-representation of women are Engineering Projects in Community Service (EPICS) and Engineers Without Borders (EWB) (Bielefeldt & Pearce, 2012).

Engineering Projects in Community Service (EPICS)

EPICS originated at Purdue University and has been successful in attracting women for over two decades. The EPICS student population has been more diverse than the overall college population. From 2014-2016, the 120-person first-year cohorts were 44% female compared to 25% in the overall engineering population (Oakes et al., 2018). One study of 8 women found the following reasons for why they chose to participate in EPICS: as a way to gain authentic engineering experience in a setting that is comfortable to them, as a way to help others, and the team/community environment, which offers social interaction and a support group (Matusovich et al., 2013). A larger follow up study of 757 students confirmed these reasons and found a disproportionately positive impact on retention of females (Oakes et al., 2018).

Engineers Without Borders (EWB)

EWB is a prominent engineering service learning organization. A case study of the University of Colorado at Boulder EWB chapter found that from 2002-2005, women comprised 41% of 61 active participants and 40-62% of the leadership board, much higher than the 26% expected based on the majors represented (Bielefeldt, 2006). Several studies of EWB members, one of 505 members (215 female) and another of 105 members, found that a significantly larger percentage of females mentioned humanitarian emphasis as motivation and important knowledge when compared to males (Litchfield & Javernick-Will, 2014, 2015). This study also found that females showed gains previously identified as important for engineering persistence, particularly relationships: women value the social elements in engineering, such as teamwork and community. These findings align with the results found in the studies of the EPICS program.

8. RECOMMENDATIONS

Current historical factors make the integration of sustainability into engineering education viable. For example, ABET 2000 criteria have significant nontechnical emphases that include sustainability. There have also been changes in the institutional landscape, such as NSF funding and NAE programs and workshops that target sustainability, as well as rapid growth of sustainability-oriented student organizations (e.g., EWB, ESW). Industry, regulatory, accreditation, and student demand for sustainability in engineering education continues to grow. A one-size-fits-all approach for integrating sustainability into engineering education may not work given the uniqueness of different institutions, but here I provide several recommendations based on various case studies of systemic change across diverse contexts.

Leverage Other Reforms, Crises, and Market Positioning to Catalyze Change

Curricular reforms (e.g., to meet accreditation criteria), crises (e.g., enrollment, funding), and market positioning (e.g., rankings) provide an opportunity to enact other changes to the curriculum. Many cases of successful systemic curricular change have arisen by hitchhiking onto other reforms. University ranking systems provide incentive for institutions to position themselves in a particular way. One emerging market positioning opportunity is the new Carnegie Classification, which ranks universities based on how well they contribute to social mobility (Mangan, 2022). Since engineering promotes greater social mobility than other disciplines (Bailey et al., 2021), an opportunity could be created by touting the promise of sustainability to attract and retain women and underrepresented racial minorities.

Adopt an “Integrated” or “Rebuild” Approach to Incorporating Sustainability

To facilitate deeper student understanding of sustainability, integrate it at multiple locations throughout the curriculum (e.g., engineering sciences courses, design courses, etc.). This requires either an “integrated” or a “rebuild” approach to incorporating sustainability. An integrated approach involves embedding sustainability into several existing courses. A rebuild approach involves redesigning the curriculum. One barrier to integration of sustainability is a perceived lack of space in the curriculum. However, this is based on the faulty logic of the “coverage” model, which assumes greater coverage of content translates into greater student learning, but this has been debunked (Leydens & Lucena, 2017). Instead, students are more likely to retain knowledge when it is contextualized in a real-world application. If a stand-alone, add-on course is the only option, design courses are the best “location” for sustainability.

Foster Both Top-Down and Bottom-Up Change, with the Department as the Driver

Curricular change is generally faster, more coherent, and more holistic when the process is triggered at an institutional level, and slower when initiated by individual faculty. However, it is vital to establish a sense of responsibility for integration all over the institution. Strong personal and/or formal linkages between students, faculty, staff, and administrators can link top-down and bottom-up processes and facilitate communication. Change leaders should identify and support existing faculty “sustainability champions.” Targeted implementation to address the particular assumptions of other faculty members with varying attitudes toward sustainability will likely be more effective than a one-size-fits-all approach.

Employ “Organizational Development” and “Faculty Learning Communities” Strategies

The most appropriate and effective strategies will depend on the particular context, but in general, two strategies seem to be most effective, especially when used in combination with each other. The first strategy, “Organizational Development,” falls into the category of enacting policy, and it aligns with a top-down change process. The change leader develops a new vision, strategy, and structures for aligning stakeholder attitudes and behaviors. Promising structures include funding, faculty working groups, and a center in charge of sustainability change processes. A promising policy reform is to reward faculty participation in sustainability efforts.

The second strategy, “Faculty Learning Communities,” falls into the category of developing reflective teachers, and it aligns with a bottom-up change process. The “implementation” (aka “teach-the-teacher”) strategy can trigger resistance from faculty because it infringes on their sense of autonomy for their courses and their desire to protect the boundaries of their discipline. The specific “faculty learning communities” strategy known as the “Individual Interaction Method” (aka “ask-the-teacher”), which involves face-to-face discussions and workshops where faculty are invited to suggest how their own (sub-)discipline and courses might contribute to sustainability, has been much more successful.

Use Project-Based Service-Learning to Enhance Learning, Inclusivity, and Branding

Project-based learning (PBL) and project-based service-learning (PBSL) are the most effective teaching methods for both facilitating student learning about sustainability and recruiting and retaining women and underrepresented minorities. These transformative learning processes also help learners become aware of unconscious ideologies and mindsets and may promote cultural paradigm shifts in engineering. PBL and PBSL are also a promising public relations and fundraising tool, as administrators love to tout civic engagement and philanthropic donors are more likely to support initiatives with positive social impact (Leydens & Lucena, 2017).

9. GAPS AND FUTURE RESEARCH

I have identified three primary gaps in the literature that provide directions for future research. (1) The first gap is related to industry. Historically, there has been a general lack of concern, or even conflict, regarding sustainability within industry along with concerns about the employability of sustainable engineers who might oppose the status quo. What are current industry perspectives and practices regarding sustainability? (2) The second gap pertains to lobbying powerful stakeholders. None of the case studies explicitly mentioned this strategy. However, stakeholders such as ABET, the NAE, and the relevant professional body for each particular discipline could be powerful driving forces for integrating sustainability into the curriculum. How might we effectively lobby powerful stakeholders? (3) The third gap is about justice, equity, diversity, and inclusion. JEDI in engineering education has largely centered on women rather than other historically underrepresented minorities (URMs). Additionally, the community-engaged learning programs described in this report are attracting a higher proportion of women unintentionally. How might we intentionally design programs to attract women and other URMs?

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APPENDIX

Table A1. Universities where sustainability implementations have occurred in Africa and Asia.

Country	University	Discipline(s)
Hong Kong	Hong Kong Polytechnic University	Civil
Oman	Sultan Qaboos University	Civil
South Africa	University of Cape Town	Chemical
Taiwan	National Pingtung University	General
Taiwan	Tajen University of Technology	General

Table A2. Universities where sustainability implementations have occurred in Australia.

Country	University	Discipline(s)
Australia	Curtin University	Civil, General, Mechanical
Australia	Monash University	Chemical
Australia	RMIT University	Chemical
Australia	Swinburne University	Product Development
Australia	University of Sydney	Civil

Table A3. Universities where sustainability implementations have occurred in Europe.

Country	University	Discipline(s)
Denmark	Aalborg University	Environmental, General
Denmark	Technical University of Denmark	General
France	University Joseph Fourier	Civil
Germany	Technical University Berlin	Chemical
Greece	University of Thessaly	Civil & Environmental
Ireland	Limerick University	General
Lithuania	Kaunas University of Technology	Environmental
Poland	Technical University of Lodz	Production
Spain	Politechnical University Valencia	Civil
Spain	Technical University of Catalonia	General
Sweden	Blekinge Institute of Technology	General
Sweden	Chalmers University	Civil & Environmental, General, Mechanical
Sweden	Malardalen	Environmental
Sweden	Royal Institute of Technology	Environmental
Sweden	University of Kalmar	Environmental
The Netherlands	Delft University of Technology	General
The Netherlands	Erasmus University	Environmental
United Kingdom	Cambridge University	General
United Kingdom	Imperial College London	Environmental
United Kingdom	Newcastle University	Chemical
United Kingdom	University of Leeds	Environmental
United Kingdom	University of Manchester	General
United Kingdom	University of Plymouth	General
United Kingdom	University of Wolverhampton	General
Ukraine	Kiev Polytechnic Institute	General
Ukraine	State University of Chemical Engineering	Chemical
Vienna	Vienna Institute of Technology	General

Table A4. Universities where sustainability implementations have occurred in North America.

Country	University	Discipline(s)
Canada	Queen’s University	Civil
Canada	University of British Columbia	Mining
Canada	University of Calgary	General
Mexico	Universidad Autónoma Metropolitana	General
USA	California Polytechnic State University	Electrical, Materials
USA	Catholic University of America	Civil
USA	Clemson University	-
USA	Colorado State University	Civil
USA	Florida A&M University	Civil
USA	Georgia Institute of Technology	Civil & Environmental
USA	Iowa State University	General, Materials
USA	James Madison University	General
USA	Kettering University	General
USA	Michigan Technological University	Civil & Environmental
USA	Oregon State University	Mechanical
USA	Pennsylvania State University	Architectural
USA	Purdue University	General
USA	Rose-Hulman Institute of Technology	Civil
USA	United States Air Force Academy	General
USA	University of California, Santa Cruz	General
USA	University of Colorado	Civil, General
USA	University of Florida	Materials
USA	University of Missouri	Civil
USA	University of Nebraska	Civil & Environmental
USA	University of New Haven	General
USA	University of Oklahoma	General
USA	University of South Carolina	-
USA	University of Texas at Arlington	Civil
USA	University of Toledo	Civil
USA	Washington University	Engineering Design
USA	Worcester Polytechnic Institute	Materials