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Multistage Sustainability Education for University Engineering Students: A Case Study from Mechanical Engineering in Technological University Dublin*

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Sustainability will be a key challenge that future engineering graduates must consider when solving problems. This paper sets out the approach taken in the mechanical engineering discipline of Technological University Dublin (TU Dublin) to help students acquire and develop the requisite skills to integrate aspects of sustainability when tackling engineering problems. The approach, which has already been implemented across a number of different design and innovation modules, consists of two distinct phases. In the first, students are educated about sustainability and related issues. In the second phase, students are educated for sustainability and are taught to identify, define and solve problems so they can plan, develop and implement solutions to complex sustainability challenges/problems. Implementing this approach has raised questions, particularly in relation to helping students deal with conflicting requirements, understanding the limitations of their own knowledge, and the relationship between ethics and sustainability. Engineering educators will need to address such questions as they develop their approach(es) to sustainability education.

Keywords: sustainability education; multistage; mechanical design

1. Introduction

In 1713 a German forestry handbook introduced a new word: Nachhaltigkeit [1]. In English, the word was translated as "sustained yield" and referred to the practice of harvesting just enough trees each year to ensure the forest would naturally regenerate in future years. The term "sustained yield" found its way into English forestry publications about 100 years later. In time, Nachhaltigkeit's meaning expanded from protecting forests to protecting animals, fish, plants, and other food items. Accordingly, the practice suggested that just enough animals would be hunted and fish caught to ensure continuity of future generations of these species.

This concept of sustainability aligns with the report, "Our Common Future", published by the Bruntland Commission (formally the World Commission on Environment and Development) which defined "sustainable development" as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" in 1987 [2]. This report defined "needs" specifically in terms of prioritizing the essential needs of the world's poor.

Sustainability is considered one of the greatest challenges of our time and is enshrined in the seventeen Sustainable Development Goals (SDGs) unanimously adopted by all United Nations (UN) member states in 2015 [3]. This is one of the most ambitious and important global agreements in recent history and is built upon previous global sustainability efforts such as The Millennium Goals [4]. The SDGs constitute a call for action by all countries to promote prosperity and fairness while protecting the environment and ensuring that future generations will be able to meet their needs. Many of these sustainability challenges, sometimes referred to as "wicked problems", will be socially complex and difficult to define and will need to be solved with contradictory or incomplete data.

Engineers are uniquely positioned in society to engage and implement the UN SDGs due to their problem solving competences and specialised technical knowledge. Solutions to sustainability challenges are costly to implement and many cannot be fully tested without implementation, and implementation might even cause new problems. As a result, engineering graduates must adopt a stance of sustainability in their work as well as being technical problem solvers. Consequently universities, and other bodies involved in educating engineers, have responsibility for achieving the UN SDGs. Professional bodies such as Engineers Ireland, who accredit engineering programs in Ireland, have reflected this importance by including specific sustainability criteria in their accreditation requirements [5]. In response to political trends and societal expectations, sustainability efforts are increasingly tied to opportunities for accessing government funding supports such as grants. Funding calls can be focussed on specific sustainability-related challenges and/or the application can demand a particular justification relating to sustainability [6].

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Sustainability efforts also reflect well on university rankings. Several specialised thematic rankings are now available which, according to Peterbauer [7], give increased visibility to institutions that might have been at a disadvantage in the more established international university rankings. Examples include the sustainability-focused UI GreenMetric World University Rankings [8] and the Times Higher Education Impact Rankings [9] which incorporate and evaluate the extent to which universities are working to achieve the UN SDGs. Based upon results released in April 2022 TU Dublin has been positioned in the 101$\sim$200 bracket (up from the 201$\sim$301 bracket in 2021) of the Times Higher Education Impact Rankings [10]. Such rankings are closely watched by students and are important for student recruitment.

The sustainability performance of companies is also increasingly assessed by investors and employees. One example is the Dow Jones Sustainability Indices (DJSI) launched in 1999 [11]. This family of indices, evaluating the sustainability performance of thousands of companies trading publicly, is based on an analysis of corporate economic, environmental and social performance. Issues such as corporate governance, risk management, branding, climate change mitigation, supply chain standards and labour practices are assessed in calculating the indices.

From a stakeholder perspective, there is an increasing expectation that engineering graduates must learn about sustainability and how to address the challenges and opportunities that it presents. Efforts to do so are inherently complex, requiring revisions to curricula, working processes and procedures, and sustained engagement and collaboration that require academic and organisational support. Integration of the SDGs into university culture must be carefully managed so that students develop professional and technical expertise with a true understanding of sustainability principles.

This paper describes an approach implemented by the Mechanical Engineering discipline in the School of Mechanical Engineering in Technological University Dublin (TU Dublin) to help students experience and develop the requisite skills to address sustainability problems. TU Dublin is Ireland's first Technological University and offers educational options from level 6 to level 10 on the Irish National Framework of Qualifications (NFQ) [12]. Representing the University's commitment to sustainability, TU Dublin's strategic plan was developed through the lens of the Sustainable Development Goals and is crafted around three pillars of People, Planet and Partnership [13]. The approach described below has been applied to three courses in mechanical engineering at level 7 (Ordinary Bachelor's degree), level 8 (Honours Bachelor's degree), and level 9 (Master's Degree). Upon successful completion of their level 7 studies a substantial percentage of students progress immediately to the level 8 degree. A smaller percentage of level 8 students will begin the level 9 degree immediately upon graduation while others will enter industry. The level 9 Master's degree can be taken full-time or part-time.

2. "What to Teach?" and "How Should we Teach?": A Concise Review of the Literature on Sustainability Education

To be truly effective in the workplace students must acquire appropriate competences and cultivate different perspectives so they can deal with complex problems like sustainability. The competences and attributes which students develop must align with real world needs. Developing these skills requires significant changes to the traditional curricula for design engineers [14]. More specifically it involves understanding the requirements and expectations of engineering academics, engineering students and engineering employers.

There is a significant body of research relating to the education of future generations of professionals for sustainable development. A significant portion of this work involved identifying graduate attributes to better deliver sustainable development, for example by Lozano et al. [15] and Ortiz et al. [16]. The International Engineering Alliance (IEA) has published the approved revised Graduate Attributes and Professional Competencies (GAPC) Framework [17]. The United Nations Educational, Scientific and Cultural Organization (UNESCO) and the World Federation of Engineering Organisations (WFEO) have supported this work. In the Irish context Engineers Ireland's accreditation framework is strongly aligned with the new IEA graduate attributes.

As part of an EU Erasmus+ project, Beagon et al. [18] conducted focus groups with engineering academics, engineering students and engineering employers from Ireland, France, Denmark and Finland. Focus groups were split into three distinct sessions, each with a different list of specific research question(s). The first of these was to determine the current extent of knowledge (of academics, students and employers) about Sustainable Development (SD) in general and the SDGs in particular. The second related to current SD activities within engineering programs and the third was to identify skills and competence requirements for the future. A model developed as part of this work proposes three key pillars of engineering skills and attributes to meet the SDGs: technical skills, non-technical skills and attitudes [19]. These are further subdivided into categories with lists of skill sets under the following headings: fundamental technical skills, application skills, outward facing – people orientated skills, inward facing – ways of thinking, worldview and character and ethical orientation.

Multiple researchers have reported lists of skills, transferable competences and graduate attributes that they believe future graduate engineers will need to solve sustainability challenges. Although the exact terminology might vary, significant overlaps exist between the content of these lists. All highlight the need for strong fundamental technical skills as a core recommendation.

There is a clear rationale for the integration of sustainability and the SDGs into engineering programs and they are central to the TU Dublin Strategic Plan [13]. Sustainability was implicitly present in mechanical engineering courses for many years across a range of different modules. However it has been taught in a piecemeal and discipline-, or topic-specific, fashion. In many cases, the actual definition of sustainability might not have been made clear to students and the focus may have been limited to describing environmentalism. For example, students may have learned about an application to optimise the control of an internal combustion engine so that fuel consumption is minimised, but they might not have considered other alternatives or fully contextualised the application.

Since the adoption of the SDGs, organisations at national, European and global levels have produced guides to help those teaching a range of age groups. For instance, UN-related websites contain a large quantity of resource material for teachers and parents who want to teach children about the SDGs in a clear understandable manner [20]. Cartoon characters are used to explain the SDGs to younger children and create awareness of the importance of sustainability.

The National Council for Curriculum and Assessment in Ireland, with responsibility for early childhood, primary and post-primary level, has mapped the curriculum frameworks to UNESCO's key competencies for sustainability. Opportunities for teaching and learning about the SDGs across school levels have been identified [21].

From a university perspective, the Sustainable Development Solutions Network (SDSN) in the Australia/Pacific region highlights how universities can contribute to the SDGs in terms of their learning, teaching, research, organisational governance, culture, operations and external leadership [22]. Case studies from various contributing universities in the region are presented and show a range of approaches taken to integrate sustainability into engineering courses.

Different frameworks have been proposed to help universities embed sustainability and other climate change education into their curricula. One such framework, proposed by Molthan-Hill et al. [23], detailed four different approaches:

(i) *Piggybacking:* this describes where SDG education is explicitly integrated into existing modules and courses. An example is a case study integrated into a module. This is referred to as the diffusion model by some authors [24] and considered the most accessible approach for many universities.
(ii) *Mainstreaming:* integrates SDG education into existing structures with an emphasis on a broader cross-curricular perspective. For example every discipline in an engineering degree could address the SDGs.
(iii) *Specialising:* refers to the creation of modules, courses or even degrees specifically relating to the SDGs. For example a course on "Sustainable Technologies in Engineering" might be created. This is referred to as the infusion model by some authors [24].
(iv) *Connecting:* relates to integrating SDGs into new cross-disciplinary offerings for all students within a university or faculty. This is sometimes referred to as transdisciplinary.

Sustainably integrating the SDGs into university operations over time represents a significant challenge. It requires significant resources to encourage all stakeholders to become aware of and engage with the desired SDG outcomes. Filho et al. [25] highlighted the need to improve engagement when they concluded that *"universities should more actively engage the student community to commit to and act in support of the SDGs"*. Any solution to the integration of the UN SDGs needs to satisfy the following requirements which can guide the integration of the SDGs into engineering courses:

(i) Ensure all stakeholders understand the need for the SDGs. This is to ensure that participants are fully engaged with the process, are fully aware of their importance, and of the difficulties associated with implementing such a cultural change within the university.
(ii) Encourage better interactions between staff and students by helping to make the expertise and knowledge of each group of stakeholders visible to everyone.
(iii) Improve knowledge sharing by allowing existing knowledge resources to be evaluated, integrated and easily accessed by all.
(iv) Create a learning environment that will contain tools to access knowledge from different sources.

Fig. 1. Structure of the approach being followed showing the two aligned phases.

Focussing more specifically on engineering design, Nickel et al. considered the introduction of sustainability and sustainable design within industry and education and listed the "size, complexity and at times redundancy of the literature on both sustainability and sustainable design" as barriers [26]. The work set out to consider how sustainability and the SDGs were operationalised in the context of design and the implications for engineering design education were addressed. Various approaches to sustainable design discussed in the literature were classified as being frameworks, methodologies, or tools. This work was completed to try and structure the literature in a way to make it more accessible, particularly for educators.

Considering the discipline of product design Watkins et al. used a series of case studies to discuss current practice in sustainable product design education [27]. The need for additional skills beyond pure design skills was highlighted and the need for students to be able to make a business case for sustainable products was explicitly mentioned. Decker et al. have considered the problem of teaching sustainability to large groups of engineering students taking mandatory courses as part of their bachelor degree [28].

Dealing with these larger groups and educating engineering students will mean change for educators. Gannon et al. surveyed engineering faculty within the United States to solicit their views on sustainability and education research [29]. The results indicate that female engineering faculty who responded felt more strongly than males about integrating sustainability into their curricula, that teaching sustainability helps students see connections between engineering and societal/global issues and that climate change is a serious threat to society.

This section has presented a brief overview of the skills and perspectives that engineering students will need to be able to address sustainability problems, and existing approaches to teaching sustainability were summarised. The next section will introduce the approach developed to teach sustainability and focus on how we are actually teaching.

3. "How we are Teaching?": a New Multistage Approach

Teaching student engineers to make a significant contribution to solving sustainability is complex, particularly when considering the differences in students' prior knowledge and the subject matter involved. In the interest of fairness to all students it must be assumed that there is very limited prior experience of sustainability. The teaching approach employed must start from this level and facilitate students to progressively build their competence and confidence. Students who might have had prior experience of dealing with sustainability are encouraged to pool their knowledge and share with their peers. A new multi-stage approach, based upon the piggybacking or diffusion model, has been implemented within the mechanical discipline of TU Dublin to structure and align teaching activities for engineering students as they progress through, and even between, their study programs.

The approach consists of two distinct phases as shown in Fig. 1. In the first phase students are educated **about** sustainability where they learn about sustainability and related issues. In this phase the focus is on raising awareness of sustainability issues and helping students to develop a common vocabulary and an ability to recognise and discuss key sustainability concepts. In the second phase students are educated **for** sustainability where they continue to map and raise awareness of sustainability issues. More importantly they will start to identify, define and solve problems in order to plan and implement solutions to complex sustainability issues.

Throughout both phases, a variety of different pedagogical techniques are used to challenge students to participate actively, think critically and reflect. This multi-method teaching approach is important due to the diversity of students (including gender, cultural background and prior experiences) on the mechanical engineering programs. Varying approaches gives students an opportunity to grow as learners and enhance their skills and capacities to learn and enhance their ability to formulate creative and appropriate solutions to challenging problems.

The remainder of this section describes these two phases in more detail. It discusses the multi-method teaching approach which has been adopted for use with students on different stages of mechanical programs within the discipline.

3.1 Teaching about Sustainability

Teaching about sustainability begins with creating awareness and gathering knowledge relating to sustainability. The objective is to get engineering students interested in, and thinking about, sustainability issues. In so doing, students are encouraged to explore their thoughts on the subject through the lens of their own experience and hence develop a sustainability mindset. Learners will increase their motivation and personal confidence to consider, express and argue for their own perspective on sustainability.

Learning in this first phase takes place along a continuum from beginner to expert and can be classified into three steps; (i) the cognitive verbal step, (ii) the associative learning step and (iii) the autonomous step [30]. As students progress through each of these learning steps the knowledge that they gain increases. This can be visually illustrated by the well-known S-curve (as shown in Fig. 2). Students can progress through these three steps at different rates. Varied pedagogical approaches support these steps.

3.1.1 Pedagogical Approach during Cognitive and Associative Steps when Teaching about Sustainability

(i) The cognitive verbal step represents the beginner's level of skill acquisition when the focus is on the mental concentration and thought processes involved in understanding and processing new information. This stage is verbal-cognitive in nature and involves the conveyance (verbal) and acquisition (cognition) of new information before a new skill can even be attempted. Terms and expressions relating to sustainability are introduced and explained as part of a technical discussion, often calling on and encouraging the students to expand on partial definitions provided by classmates. Examples of terms or expressions introduced include "sustainability", "circular economy" and "product lifecycle analysis". As part of the overall approach these terms are contextualised as part of the design process and potential design contradictions are introduced, for example:

The question might be asked "How could we make a car safer?" Several students might suggest putting in more air bags, better brakes or perhaps adding more steel into a car to make it stronger. This can lead to a discussion on what effect adding more steel might have ("What will happen if the car is heavier?") This can lead to a discussion of the efficiency of a heavier car and the effect that this will have on the larger carbon footprint that will result. The environmental issues associated with the extraction of additional materials and the associated costs can then be introduced. This can relate to direct manufacturing costs and also potential recycling costs at the end of life to dispose of additional air bag inflators or other components added.

The market pressure of trying to make a car lighter to improve efficiency, safety and running cost can be introduced. Eventually students tend to focus on the idea that adding crumple zones to the car to absorb energy without adding any additional material is a good approach to make it safer, more efficient and potentially cheaper.

Then the question can be posed. . . Who are we trying to make it safer for? Are we focussed on the car driver, the drivers of other vehicles or perhaps on pedestrians? This helps reinforce the importance of understanding the needs of stakeholders and clearly elaborating the design requirements at an early stage of the process. Sustainability must be a key element of the design process but students must still strive to empathise with and define products that will benefit stakeholders.

(ii) The associative learning step is where unrelated elements (for example, objects, sights, sounds,

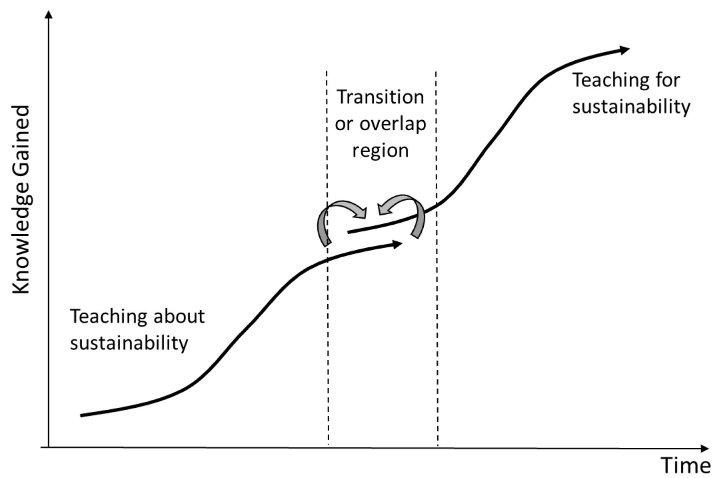

Fig. 2. S-learning curve showing the progression from teaching about sustainability to teaching for sustainability.

Table 1. Overview of the approach taken to bring sustainability to students of mechanical design

Phase of the model	NFQ level	Stage	Module Area	Step	Pedagogical approach	Typical Assessment content relating to sustainability	Individual or group?	Primary competences targeted
Phase (1) Teaching **about** sustainability	7	2	Mechanical Design	Cognitive & Associative	Case studies & examples	Multiple Choice Questions, in-class discussions and presentations.	Individual	Environmental awareness, sustainability awareness, social responsibility, curiosity.
			Mechanical Design	Cognitive & Associative	Talks by external parties & discussions	Discussion & Reflection. For example "Should you propose the use of electric hand dryers or paper towels to dry your hands in the restrooms within the university?"	Individual & Group	Critical thinking, holistic thinking, multi-perspective thinking, general knowledge, respect for others, open mindedness.
			Product Design	Cognitive & Associative	Independent research	Perform a breakdown analysis of a mass-produced consumer product with at least 3 parts. Consider the materials and processes used and consider other more sustainable options which might have been selected. Being aware of where such materials can come from and where they are manufactured serves as a basic form of Critical Sustainability Investigation and helps students understand how sustainable consumer products really are.	Individual	Lifecycle thinking, research skills, global awareness, social responsibility, environmental awareness.
			Product Design	Autonomous	Hybrid PBL	Create a game which can be used to teach young children from the ages of five to eight about (at least) one of the SDGs of your choice. How can this game be manufactured in a sustainable way? Recent examples include a model refuse truck to teach children the principles of sorting for recycling and the creation of toys to demonstrate wind, solar and clockwork energy generation.	Group	Collaboration, teamwork, empathy, design skills.
	8	2	Engineering Design	Autonomous	PBL	Design a machine to facilitate the circular economy in your local community. Considering local issues, which are often representative of global issues, can make the issues more real for students. Concept designs proposed by students in 2021-22 included designing a machine to repurpose disposable facemasks into acoustic insulation panels.	Group	Problem solving, Design Skills, conceptual understanding, resource optimisation, decision making skills, project management, organisation skills.
Phase (2) Teaching **for** sustainability	8	3	Design Projects 2	Autonomous	PBL (Student led)	PBL projects necessitating cross-discipline collaboration. Students must ty to design sustainably (through the minimal usage of materials, avoid use of non-sustainable materials) and they demonstrate the skills needed to solve sustainability problems. Over the last few years students have designed robots and a minor pivot to the project requirements has been introduced at the half-way point of the course. Students are given a press release like "The company has been taken over; our new owners want us to expand the functionality of our robots to (for example) record the co-ordinates of where it has travelled and save it on a memory stick"	Group	Multidisciplinary skills, Design skills, resource optimisation, learning to learn, Project management, organisation skills, Systems thinking, self-reflection, Agility, adaptability.
	9	Not applicable	Innovation			Students are presented with a brief which asks them to: "Identify a sustainability related problem that has been reported in the media within the last 10 days. With a group of colleagues from different engineering disciplines develop a business proposal to implement a solution to this problem. You may focus this as a non-profit or a profit seeking business idea"	Group	Innovation, Entrepreneurship, Multidisciplinary skills, Decision making skills.

ideas, and/or behaviours) become connected in our brains through **conditioning**. Examples often used in the context of promoting sustainability or "green behaviour" might include being environmentally friendly to avoid fines, social disapproval, or health issues. Such positive (or negative) reinforcement can be useful for students to learn and has application beyond sustainability issues. Students considering the effects of plastics on marine life might relate this to the behaviour of people dumping near the beach and/or the disposal of single-use plastics via incorrect channels. Through mastering associative learning principles, more complex information can be processed and students can use their internal feedback to further improve and create additional examples of (un)sustainable activities from their own experience.

- Case studies and examples are used to familiarize students with real-world sustainability problems and solutions. Reviewing websites, newspaper articles, documentaries and journal papers helps students learn about issues which they can discuss with classmates.
- Talks by external parties are arranged throughout the university and students are encouraged to attend these events or to watch the events at a later date. Recent examples include hearing food producers talk about their transition towards zero carbon solutions and the sustainability challenges associated with fast fashion. Other engineering-specific webinars, which students were invited to attend, related to pump and turbine design and how they can be designed to be more fish-friendly. An awareness of such possibilities is important for engineers as they strive to ensure that development will not negatively impact on marine eco systems.
- Students' understanding of sustainability issues has been gauged using Multiple-Choice-Quizzes over several years. More recently online subject-specific databases of multiple-choice-questions have become available. Questions, based on a content matrix and aligning with at least one of the UN SDGs, have been assessed and validated by a group of international experts [31].

3.1.2 Pedagogical Approach during Autonomous Step when Teaching about Sustainability

(iii) The autonomous step is where students perform skills consistently and accurately. They concentrate on complex tasks and information and adapt their performance accordingly.

In the second years of both level 7 and level 8 mechanical engineering programs students work on an "instructor-driven" sustainability problem as part of their design modules. The term "instructor-driven" is used to indicate that the focus is directly supported by the specifics of the module content and that it is discipline-specific to mechanical engineering. The design problems considered, which are typically narrowly focused, are developed to help students consider and critically reflect on design contradictions. The precise details of the assignments change every year but some examples from the last number of years are given below:

- Level 7 students were given the challenge of creating a game or toy to teach children from the ages of five to eight about one or more of the SDGs. The overall module is delivered as a hybrid Problem Based Learning (PBL) module. A series of traditional lectures deliver relevant technical content to students and they work on solving the problem to devise a suitable game. As part of this work the students must decide upon and be able to clearly demonstrate and defend which SDG their product is focused on. In addition, they must consider how children will interact with the game or toy and how it could be realized through manufacturing. An initiative to make assessments more authentic by getting students to prototype their designs was introduced in 2021-22 and is reported elsewhere by Treacy et al. [32].
- For Level 8 students a specific focus is placed on the circular economy. Using a PBL approach, the students must design a machine to facilitate the circular economy in their local community. Recent examples include designing a machine to sort recyclable cans, glass bottles and plastic bottles and to design a machine to refill whiteboard markers for a university. Students are expected to consider existing devices and deliver a machine-design specification, a detailed overview and flowchart of what they expect the machine to do, followed by a detailed design of each stage or module of the machine. As part of the end-of-module assessment, students propose their design to a team of "investors" to try and convince them to invest in developing the machine further.

Such student projects at both level 7 and level 8 have a sustainability focus and are specifically designed to help students learn and develop the targeted competencies listed in Table 1.

3.2 Teaching for Sustainability

As students come to the end of the learning **about** sustainability phase, they transition to the learning **for** sustainability phase. In this transition or overlap region, some similarity to the autonomous steps described in the learning about sustainability will be apparent, as illustrated schematically in Fig. 2.

During this phase, the objective is to develop the attributes and capabilities of engineering graduates so that they can actually solve sustainability problems. Examples include creativity, opportunity recognition, decision-making by critical analysis, interpersonal and collaboration skills and the actual implementation of ideas. Open-ended activities and problems play an important role in this phase.

3.2.1 Pedagogical Approach During Autonomous Stage for Sustainability

In the third year of the level 8 and the Mechanical Masters engineering programs (level 9) students work on "student-driven" problems as part of their engineering design and innovation modules respectively. The term "student-driven" emphasizes that the focus is only partly supported by the module content and that students must perform a significant body of independent work to successfully meet the module objectives. The design problems presented to students are quite broad and extend beyond the discipline of mechanical engineering. The exact details of the assignments change every year but some past examples include the following:

- Level 8 mechanical engineering students have been given the challenge of designing and building small robots since 2017 [33] and [34]. These PBL projects are not specifically focused on sustainability but do necessitate cross-discipline collaboration and give students the opportunity to develop their technical and non-technical skills and attitudes which are key skills and attributes needed to solve sustainability issues. This cross-discipline collaboration was further developed using funding made available through the TU Dublin Engineering and Built Environment programs' Teaching Champion Awards for the academic year 2021/22.
- Level 9 students from across the Engineering Faculty take a module on Innovation and Knowledge Management. Since 2020 students have developed an idea for a new business focused on the area of sustainability. This helps improve the students' ability to contextualize sustainability issues. For the 2021–22 academic year students were supported with guest lectures from a group of University-wide experts in the areas of Business, Creative Arts and Mechanical Design. This was previously reported in Session 2d of an Island of Ireland symposium [35]. The assignment format used is similar to the green business ideas competition called "Climate Launchpad" [36]. Several student groups entered this competition and one mechanical engineering group was the inaugural winner of the competition within TU Dublin in 2022 [37].

Efforts to implement sustainability into two mechanical design modules at undergraduate level and an innovation module at postgraduate level began in 2018. Implementation and refinement of the approach described has been ongoing since then. Table 1 presents an overview of the approach and includes details of the program stage the students are at, the NFQ level involved, the pedagogical approach and summary details of student assessments.

4. Putting it all Together: Practical Implementation Experience to Date

This section summarises some practicalities of the experience to date with a particular focus on the enabling elements such as the supports for staff. Aspects of the initiatives within the university, which have been focussed on this endeavour as shown schematically in Fig. 3, are also discussed. Perceived benefits for the stakeholders are also presented together with a list of issues which the author continues to grapple with in educating engineering students about and for sustainability.

4.1 Educating the Educators: Some of the Supports Available to Staff

Initiating sustainability related activities across multiple stages of an educational program invariably involves changes for the academic and the support staff involved. As mentioned previously, education for sustainability forms a central part of TU Dublin's strategic plan. Consequently several supports are available within the university to facilitate this change. Additional supports are available from national and international partners.

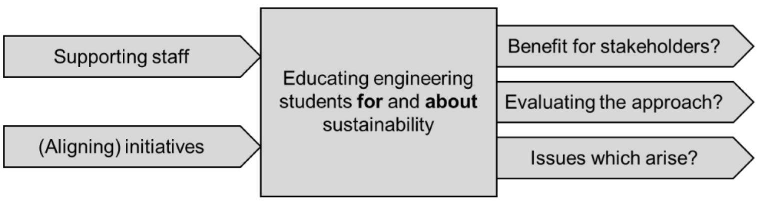

Fig. 3. Practical implementation experience to date.

Supports which staff have been able to avail of to date include:

- Community of Practice (university wide level): A group of staff who are passionate about Education for Sustainable Development from across the University formed a Community of Practice [38]. This group meets regularly to discuss their ongoing activities relating to the implementation of sustainability into education. Guest speakers from a diverse range of industries have been invited to present to staff and students. In addition, several relevant Open Education Resources (OERs) have been created and are available from a dedicated website set up by the group [39].
- Webinar for engineering educators (national level): The Academic Society within Engineers Ireland supports engineering educators throughout Ireland. This society, open to engineers and non-engineers, as well as members and non-members, was reconstituted in 2019. Academic members arrange webinars relating to topical education issues, including sustainability. This provides an extensive opportunity to see what other educators are doing, both in Ireland and internationally. It also facilitates like-minded colleagues to network with a view to future collaboration [40] and [41].
- Explanations re new accreditation requirements: As already indicated new Engineers Ireland accreditation requirements, which explicitly incorporate sustainability, were introduced in 2021 and mandated for use in accreditation events from 2022 [5]. Several opportunities to learn about these requirements have been made available to staff, both by Engineers Ireland and by TU Dublin.
- Funding initiative calls: Multiple calls for funding to improve the student experience have been made by various groups and units within TU Dublin. The author and other colleagues who deliver the mechanical design and innovation modules were awarded funding from several of these calls. This funding has been used to pilot several trials described in this paper.

4.2 Aligning the Initiatives

Multiple teaching initiatives are collectively more effective when they are mutually aligned. Since the decision four years ago to focus on educating engineering graduates to be able to more effectively deal with sustainability issues, attempts have been made to align teaching initiatives towards this objective in the area of mechanical design. These initiatives, many of which have been described earlier in this work, have benefitted the overall approach over the last few years. A schematic overview of how these were aligned to the overall approach is shown in Fig. 4.

Fig. 4 shows how different initiatives focus on different phases as the students transition from learning about sustainability to learning for sustainability. This aligns with the students' transition from NFQ level 7 all the way to NFQ level 9. The figure indicates how the expectations on students' progress from creating awareness through solving teacher-driven problems, to engaging in multidisciplinary collaboration and towards solving problems where students work independently to solve

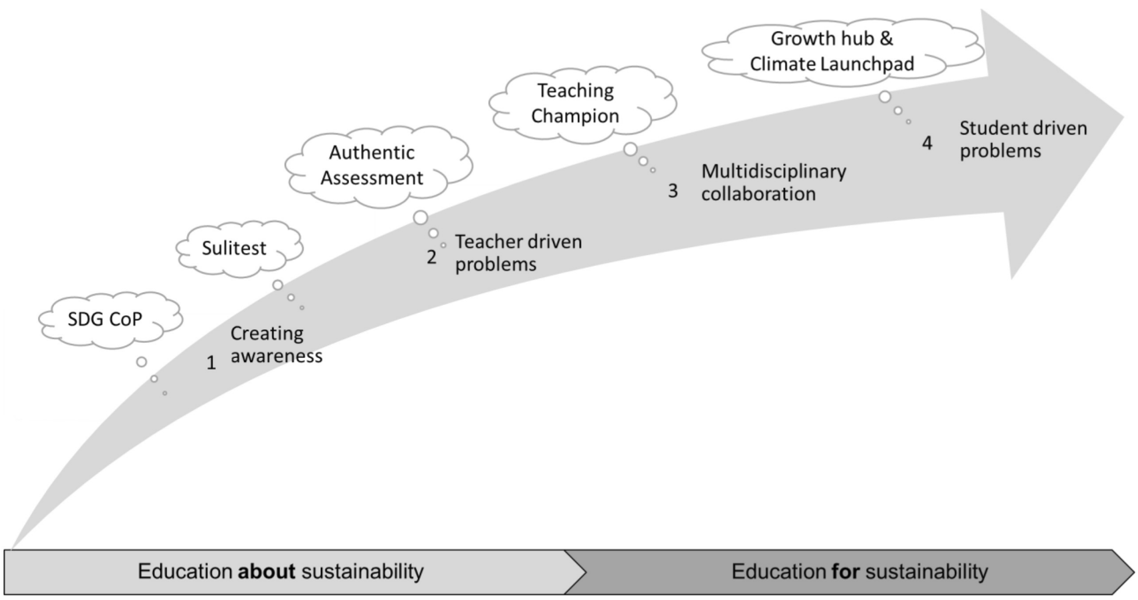

Fig. 4. How various funding call initiatives have been aligned to form the overall approach to bring sustainability to Mechanical Engineering students.

challenging, multifaceted problems relating to sustainability.

4.3 How This Will Benefit Stakeholders

The need for engineering graduates to develop attributes beyond their core technical knowledge was highlighted in Section 2. These transferable skills and values that incorporate sustainability attributes will enhance graduates' employability and societal value and are important in an increasingly complex, interconnected and uncertain world. Recent research suggests that undergraduate students are unable to appreciate the importance of these transferable skills that employers are actively seeking without being explicitly reminded of or prompted about them [42]. Mechanical engineering students in TU Dublin benefit by having this explicitly explained to them using the iceberg analogy as described in Delaney et al. [43]. The iceberg analogy is commonly used to illustrate that only a small portion of our overall knowledge (our explicit knowledge) is visible above the ocean's surface while most of our knowledge (tacit knowledge), which is typically more valuable, is not visible. This knowledge is buried in our heads and can be difficult to share since it resists being articulated.

It is important to note the competences developed in students to tackle sustainability issues are not only confined to that domain but can be transferred to other areas. Such transversal competences will also benefit employers and society. Employers will benefit by having graduates who already have the competences to meet sustainability requirements and can engineer sustainability into the products and processes that they develop.

4.4 Evaluating this Approach

The questions "what to teach?", "how should we teach?" and "how we are teaching?" in relation to sustainability have been considered. It is appropriate to consider the question "are we teaching effectively?" and how we might evaluate the overall approach. Phase 1, where students learn about sustainability, can be evaluated by considering the students' ability to answer questions, discuss, contextualise and critique SD issues and communicate their responses. This is evidenced by the output from in-class quizzes, brainstorming sessions, students presenting their thoughts to the class and other artifacts such as the machine designs or concept designs that they create. Some student outputs have been presented at the sustainability webinars organised by the Academic Society of Engineers Ireland.

The effectiveness of the "teaching for sustainability" phase is much more difficult to consider. It takes a significant amount of time for students to develop the experience and confidence to fully come to terms with solving complex and ill-defined problems associated with sustainability problems. Consideration of their coursework suggests they are developing the skills needed to solve sustainability problems while formulating solutions to open engineering problems. The specific competences targeted by each assessment are listed in Table 1. Evaluation can take place through considering their approach to such challenges and also by evaluating the performance of students on work placements and after they graduate.

Preliminary focus groups and student evaluations performed to date have been very positive. Such student surveys and focus group discussions with relevant stakeholders can help to highlight gaps in the teaching approach being taken and/or in students' knowledge. Efforts are ongoing to develop a more robust evaluation approach. Additional work is planned to develop an appropriate series of performance indicators to help quantify the effectiveness of these "teaching for sustainability" activities.

4.5 Issues which Arise with this Approach

The need for engineering graduates to develop attributes beyond their core technical knowledge has been clear for many years. This work presents details of an approach which has been successfully applied but it also raises a number of issues which must be considered, for example:

1. How to teach student engineers to deal with conflicting SDGs and understand that trade-offs will need to be made? Examples of this might include the urgent response(s) that a country makes to financial crises, pandemics or even war. Trade-offs can be needed between salaries and labour rights on one side and employment on the other [44]. Other trade-offs might include how to prioritise critical infrastructure of houses, roads or bridges, which might impact eco systems and potentially biodiversity.
2. How can we help students to learn how to prioritise among conflicting requirements; perhaps from the problem context, the country, the resource base, the geopolitical environment? For example is it better for the planet if people use water to wash a ceramic or plastic coffee cup or is it better to use a disposable paper cup? The answer might depend on multiple considerations such as what is the supply of water in the area? What will happen to the cup after use? Where was the paper pulp produced? Does it help a local farmer create additional income or does it only help a big multinational

increase profits by shipping cups to the area and increasing the carbon footprint of the cup on the way? Other examples might be to ask are paper straws for drinking really better than plastic ones if they tend to weaken during use and people try to use additional straws? How can it be appropriate to use paper straws but still have a non-compostable lid on drink cups sold in fast food outlets?

3. How can students be helped to understand the limitations of their own knowledge, or the knowledge of the team they are working with? How will they identify when there is a need to call in other experts to help with specific problems or aspects of a problem?
4. The issue of ethics and the relation between ethics and sustainability must be considered and students must understand how to navigate such issues.
5. Sustainability challenges will not be solved by technology alone and all responsibility for preparing graduates to deal with SD issues cannot be shifted to educators. We need to have spaces for dealing with sustainability but it must also be made clear that graduates alone will not have all the answers. As educators we need to connect awareness with action to avoid the risk of apathy. In doing so we must strive to educate "Global Engineers" who can think beyond simply solving purely technical problems and address the many multi-faceted sustainability challenges that the world faces.
6. This paper has described multistage sustainability education; students will progress between stages on an annual basis and as educators we must recognise that the prior learning of cohorts will change. For example future cohorts are likely to be more aware of sustainability issues due to the increasing school curriculum and media attention being given to related issues such as climate change. Benefits might accrue by surveying secondary school students to evaluate their interest and knowledge of sustainability as reported by Oswald Beiler, who also highlighted the value of the research by providing insight into attracting secondary school students into engineering [45]. In March 2022 it was announced that climate action and sustainable development would become an optional program of study for the Leaving Certificate, the second level terminal examination, in Ireland from 2024 [46].

5. Conclusions

Issues relating to SD are mainstreaming now. Changing engineering curricula to include SD learning outcomes and having graduates working on sustainability problems in industry typically takes a long time. Due to the scale and urgency of the issues there is a need to move from researching and developing SD integration objectives and aims to actually introducing and integrating them into engineering courses.

This paper contributes to this work by:

- Presenting an approach, already implemented across design and innovation modules in the mechanical discipline of TU Dublin, to guide educators on how to structure and focus their teaching activities to educate students about sustainability and for dealing with sustainability problems.
- Highlighting issues which will need to be considered to further develop and refine the introduction of sustainability education for engineering students.

The discipline of mechanical engineering has implemented multiple initiatives to integrate sustainability throughout the design modules offered. It is hoped that the work described here will inspire further discussion and feedback from engineering educators. Evaluation of the effectiveness of the approach described in this paper, particularly for the education for sustainability, has been somewhat limited. A more in-depth evaluation will be the topic of future work.

ABBREVIATIONS USED

DJSI:	Dow Jones Sustainability Indices
EU:	European Union
GAPC:	Graduate Attributes and Professional Competencies (Framework)
IEA:	International Engineering Alliance
NFQ:	National Framework of Qualifications
PBL:	Problem Based Learning
SD:	Sustainable Development
SDGs:	Sustainable Development Goals
SDSN:	Sustainable Development Solutions Network
TU:	Technological University
UN:	United Nations
UNESCO:	United Nations Educational, Scientific and Cultural Organization
WFEO:	World Federation of Engineering Organisations

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