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Sustainable Product Design Education: Current Practice

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Abstract
Current production and consumption patterns are unsustainable, causing irreversible damage to the environment and human health and well-being. Designers play a vital role in resolving this problem — their decisions affect product manufacturing, distribution, use, and disposal — and hence they must be aware of the positive and negative impacts of their design decisions. Sustainable product design education is key to developing the knowledge, skills, and responsibility required for future generations of product designers and their educators to make informed and responsible decisions within their practice, and also enhance the social and environmental performance of their creations and effectively communicate the value of such decisions within a commercial context. In this article, we present insights and challenges in contemporary sustainable product design education in higher education. We document the experiences of six academics involved in teaching and researching sustainable product design in the United Kingdom, Australia, Denmark, the Netherlands, and the United States. We hope to provide a useful reference for academics seeking to adopt sustainable product design practices in their existing programs, develop new sustainable product design education programs, or reflect on their own existing product design practice.

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Introduction

Today's global production and consumption patterns are causing irreparable social and environmental damage. Vast inequalities exist between developed and developing countries. Unless such patterns are rapidly addressed, the negative consequences will be irreversible.[1] Design plays a critical role in helping to reduce negative social and environmental impacts because designers' decisions are responsible for the impact of the goods and services we consume. Around 80% of the environmental impact of a product is defined at the early (design) stages of the product development process.[2] Designers are responsible for specifying products' material compositions, how their raw materials are processed or formed (manufactured), and how products are packaged, distributed, used (to a certain extent) and eventually disposed of. Every decision made during the design of a product or product-service system will have a direct (negative or positive) social and environmental impact upon people and our planet. Sustainable product design (SPD) is situated in the context of increasing concern for the degradation of the planet, the availability of resources for future generations,[3] and the impact of these phenomena on humans and on society. Its roots lie in the early environmental movement heralded by Rachel Carson's *Silent Spring*,[4] but its remit includes the wider social concerns Victor Papanek asserted in his seminal wakeup call for designers *Design for the Real World*,[5] as well as in Tomás Maldonado's early work,[6] and later work by Carlo Vezzoli and Ezio Manzini.[7] Sustainable product design thus uses a holistic and evolved approach. The early notions of environmentally responsible design — design for the environment, eco-design — are components of the approach, but it also takes wider societal needs and implications into concern. Sustainable product design uses a triple bottom line[8] approach — its 3Ps are "planet, profit, and people," balancing environmental concerns, with societal responsibility and economic profit. This is consistent with the goals explored by *Our Common Future*,[9] the UN's Decade of Education for Sustainable Development 2005–2014,[10] and more recently its Sustainable Development Goals (SDGs).[11]

Sustainable product design education is vital at all stages of design education but particularly in higher education (HE), where training, educating, and instructing students takes place prior to their commencing design careers in industry. While there are countless studies on sustainable product design education, and its implementation via different methods,[12] researchers typically tend to focus on single institutions or specific course design.[13] We take a more holistic approach in this article, presenting the individual experiences, opinions, and challenges expressed by experienced academics at different institutions and countries. All are active in both research and teaching in the area of sustainable product design. Our aim is to provide an overview of current sustainable product design practice (teaching and research) to academics and academic departments wishing to implement, develop, or reflect on sustainable product design in their programs and courses. We reveal the differences in the types of skills and knowledge required for sustainable product design education, versus those taught generally in product design. To teach these competencies, specialist academic educators must effectively communicate

1 Ove Hoegh-Guldberg et al, "Impacts of 1.5 °C Global Warming on Natural and Human Systems," in *Global Warming of 1.5°C: An IPCC Special Report*, ed. Valérie Masson-Delmotte et al. (Geneva: Intergovernmental Panel on Climate Change, 2018), 175–311, https://www.ipcc.ch/sr15/chapter/chapter-3/.

2 Tim C. McAloone and Niki Bey, *Environmental Improvement through Product Development: A Guide* (Copenhagen: Danish Environmental Protection Agency, 2009), 5, available at https://backend.orbit.dtu.dk/ws/portalfiles/portal/3996106/mpu-elektronisk-uk.pdf.

3 WCED, "A Threatened Future," in *Our Common Future: Report of the World Commission on Environment and Development* (Geneva: World Commission on Environment and Development, 1987), chapter 1, available at https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf.

4 Rachel L. Carson, *Silent Spring* (New York: Houghton Mifflin. 1962).

5 Victor J. Papanek, *Design for the Real World: Human Ecology and Social Change* (New York: Bantam Books, 1971).

6 Tomás Maldonado, *Design, Nature, and Revolution: Toward a Critical Ecology* (New York: Harper & Row, 1972).

7 Carlo Vezzoli and Ezio Manzini, *Design for Environmental Sustainability* (London: Springer, 2008).

8 John Elkington, *Cannibals with Forks: The Triple Bottom Line of 21st Century Business* (Oxford: Capstone, 1997).

9 WCED, "Towards Sustainable Development," *Our Common Future: Report of the World Commission on Environment and Development* (Geneva: World Commission on Environment and Development, 1987), Chapter 2, available at https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf.

10 United Nations, *United Nations Decade of Education for Sustainable Development* (New York: United Nations General Assembly, 2002), https://digitallibrary.un.org/record/482207.

11 United Nations, *Transforming Our World: The 2030 Agenda for Sustainable Development* (New York: United Nations General Assembly, 2015), https://digitallibrary.un.org/record/3923923.

12 Daniel Christian Wahl, *Designing Regenerative Cultures* (Dorset: Triarchy Press, 2016).

13 Carlo Vezzoli, "A New Generation of Designers: Perspectives for Education and Training in the Field of Sustainable Design: Experiences and Projects at the

and assess complex subject knowledge with suitable rigor. A challenge in HE is ensuring that academics and teaching staff are employed, or suitably trained, to deliver such content. Furthermore, a higher priority must be placed on including sustainable product design education in design curricula overall, to ensure that it is effectively resourced and not minimized or otherwise dumbed down due to a lack of specialized knowledge or staff.

Methodology

We used a multiple case study approach[14] in this article, and adopted qualitative research methods to draw insights from academics representing six HE institutions (Nottingham Trent University, Cranfield University, Dartmouth College, Technical University of Denmark, Technical University of Delft, and University of New South Wales) from five countries (the UK, Australia, Denmark, the Netherlands, and the USA). To identify academics who could provide insight and expertise in sustainable product design, we used the following selection criteria:

i At least eight years' experience in sustainable product design in teaching and/or research
ii A breadth of experience in HE teaching, encompassing both undergraduate and postgraduate courses
iii Representation from more than one country or continent
iv Relevant publications within the field of sustainable product design

Next we will introduce each institutional case study.

Nottingham Trent University (NTU) — UK

This case study, considers the teaching of sustainability to undergraduates on a BSc product design degree, engineering students undertaking an Erasmus semester, and related content in doctoral supervision. In the BSc course, teaching is predominantly delivered through two studio projects the 2nd year (n ~ 40 students) and a final year capstone project (n ~ 40 students) applying the theory taught across all three years of the course. The 2nd year projects feature social and environmental considerations and approaches, with at least one project completed for each, typically a life cycle assessment (LCA) redesign project and another concerning design for the developing world addressing aspects of the SDGs. Capstone projects are largely selected by students from a wide range of briefs, but these typically address aspects of the SDGs and specific sustainability assessment criteria. The Erasmus semester is delivered to European exchange students as part of the European Project Semester,[15] and includes a compulsory element on sustainability. Content is delivered to multidisciplinary groups of design and engineering students (n ~ 30 students), who consider the redesign of an existing electromechanical product using sustainable design strategies and LCA tools. Furthermore, academics have experience in supervising numerous doctoral students all with a sustainability focus, that have close alignment with industry.

Politecnico Di Milano University," *Journal of Cleaner Production* 11, no. 1 (2003): 1–9, DOI: https://doi.org/10.1016/S0959-6526(02)00057-4; Deniz Deniz, "Sustainable Thinking and Environmental Awareness through Design Education," *Procedia Environmental Sciences* 34 (2016): 70–79, DOI: https://doi.org/10.1016/j.proenv.2016.04.008; Debra Lilley and Vicky Lofthouse, "Teaching Ethics for Design for Sustainable Behaviour: A Pilot Study," *Design and Technology Education: An International Journal* 15, no. 2 (2010): 55–68, available at https://ojs.lboro.ac.uk/DATE/article/view/1493; Lora Oehlberg, Ryan Shelby and Alice Agogino, "Sustainable Product Design: Designing for Diversity in Engineering Education," *International Journal of Engineering Education* 26, no. 2 (2010): 489–98, available at http://best.berkeley.edu/wp-content/uploads/2015/07/32_Ijee2282.pdf; Vicky Lofthouse, "Preparing the Way for Mainstream Sustainable Product Design," *Form Academic Forskningstidsskrift for Design Og Designdidaktikk* 10, no. 2 (2017): 1–19, DOI: https://doi.org/10.7577/formakademisk.1657.

14 Robert K. Yin, *Case Study Research and Applications: Design and Methods*, 6th ed. (Thousand Oaks, CA: SAGE, 2018), 90–97.

15 For more information, see http://www.europeanprojectsemester.eu; Abel J. Duarte et al, "Engineering Education for Sustainable Development: The European Project Semester Approach," *IEEE Transactions on Education* 63, no. 2 (2019): 108–17, DOI: https://doi.org/10.1109/TE.2019.2926944.

Cranfield University — UK

This case study considers the content of teaching delivered to students of the Master's in design thinking at the Centre for Competitive Design (C4D).[16] The program aims to develop future design leaders by equipping them with the skills and competencies they need to make a valuable contribution to future societal challenges. The program has a specific "Whole Systems Design" module, which introduces students to strategies and tools that enable integrated, sustainable, circular product development. Tools taught in this module include life cycle thinking, circular design, circular business models, design for sustainable behavior, social sustainability, and systems thinking. Students gain experience from real-life scenarios requiring a holistic approach to design for improved sustainability; they are expected to complete an industry-led group project and an individual project. The group project trains students in teamwork and asks them to develop non-technical skills as part of the taught program. The individual project encourages students to develop their research capability, depth of understanding, and ability to provide world-class solutions to real problems through design strategy and leadership.

Dartmouth College — USA

This case study is focused on the postgraduate industrial ecology engineering module: one of two sustainable design/engineering electives available at Dartmouth with approximately 12–18 students per year. This module on sustainable design engineering also includes sustainable design entrepreneurship and business model design. This course includes a range of sustainable design tools and addresses key areas such as energy effectiveness, circularity, product-service systems, materials selection, biomimicry, design for behavior change, and end of life perspectives. The module is project-based, requiring student teams to work with an external business and a business school team to develop a product using relevant sustainability tools and methods. Assessment takes place through team-based project presentations and reports. Course redevelopment was partly funded by a VentureWell grant, a non-profit organization that encourages entrepreneurship in engineering students.

Technical University of Denmark (DTU) — Denmark

An undergraduate bachelor's course entitled "Product Life Cycle and Environmental Issues," established over two decades ago at DTU, was our focus for this case study. The course is offered to students in a wide range of engineering programs at the university; in 2020 there were 150+ students enrolled across seven engineering programs (such as BSc Design & Innovation, BSc Architectural Engineering, BSc Mechanical Engineering, and BSc Strategic Analysis & System Design). The course starts with an overview of the key trends shaping sustainable design (the circular economy, or the SDGs for instance) and an overall discussion of the need to consider sustainability during the early stages of the design process. This is supported by the use of a reference model[17] for sustainable design, which introduces a number of tools and approaches to guide the design process towards more sustainable products. The final assignment of the course is a design project: students are asked to plan the eco-design process for a given product, select the most appropriate

16 For more information, see https://www.cranfield.ac.uk/courses/taught/design-thinking.

17 Tim C. McAloone and Daniela C. A. Pigosso, "Ökodesign: Entwicklung von Produkten mit verbesserter Ökobilanz," in *Pahl/Beitz Konstruktionslehre: Methoden Und Anwendung Erfolgreicher Produktentwicklung*, ed. Beate Bender and Kilian Gericke (Berlin: Springer, 2021), 975–1021, DOI: https://doi.org/10.1007/978-3-662-57303-7_22.

methods and tools, identify the key environmental impacts along the product life cycle, and identify design guidelines and associated sustainability performance indicators to guide the design process.

Delft University of Technology (TU Delft) — The Netherlands

Our Delft case study examined the compulsory "Design for Sustainability" module for second-year undergraduates in industrial design engineering (~ 350 students). It is one of six sustainable design/engineering modules available in the department, but most others are elective or postgraduate modules. This module includes content on the UN SDGs; the Triple Bottom Line; design for sustainable behavior change; material selection; material recovery strategies; LCA; and the economic, technical, and environmental feasibility of using renewable energy (in particular solar energy) for powering products. This module is team-taught by four instructors, alongside several coaches and teaching assistants, with each instructor leading a two-week portion of the course. The class is theory-based; it consists of formative group-based (non-graded) homework assignments and quizzes, with an individually-graded final exam. On completion, students are encouraged to apply sustainability tools and methods in future projects and modules, and future course revision is planned to further strengthen this connection.

University of New South Wales (UNSW) — Australia

The case study covers the teaching of design for sustainability within a 3-year Bachelor of Industrial Design degree with an additional 1-year honors option. The program is mid-sized by Australian standards, with ~ 50 students enrolled each year, 40% of which are international. Standard courses run over a 10-week trimestral term, typically with 3 or 4 hours of face-to-face contact every week. Design studio courses are regarded as the backbone of the degree, with theory courses and skills courses complementing the studio courses. Students are required to complete 8 studio courses during the 3-year degree. Since 2013, design for sustainability has been the focus of at least one design studio in the second and third years. Projects in these year levels encompass various aspects of environmental sustainability and social sustainability, such as the Australian National Packaging Targets (100% reusable, recyclable, or compostable packaging by 2025), the UN Decade of Healthy Ageing 2021–2030, the SDGs of 2015–2030, and the 2000–2015 Millennium Development Goals that preceded the SDGs. The range of topical design challenges offered in these studio classes has included collaborative consumption, sustainable product-service systems, circular economy, crime, disaster resilience, developing world, and biomimicry. In the honors year, students align their capstone projects with the research interests of academic staff, and each year a few project themes are offered in design for sustainability topic areas.

Data Collection

We gathered insights from the answers to a series of six open-ended questions which were delivered in a semi-structured interview format to gather responses on the breadth, content, and style of the instructor's teaching of

Table 1 **Types of modules including sustainable product design content.**

	Practice	Theory
Undergraduate	- Final year projects (capstone) - Technical thesis - 2nd-year studio projects - Erasmus exchange group projects - Design and innovation	- Final year dissertations - Biomimicry course - Product life and environmental issues
Taught Postgraduate	- Circular design models and business models - Group projects - Individual projects	- Dissertations - Industrial ecology - Systems thinking - Design for social sustainability - Design for sustainable behavior - Life cycle assessment
Other	- Doctoral supervision	

sustainable product design. These responses were used as a starting point for further comparison and discussion with the academics to distill the key points for inclusion in this article.

The rationale for this data collection method was to enable rich qualitative data to be captured—that is, informed by experienced academics in sustainable product design, from differing higher education systems. The following six questions were asked to each academic:

1 What are the key competencies sustainable product designers graduating in 2025 should have, and why are they of value?
2 What concepts and skills do you teach to develop these competencies?
3 What teaching pedagogies do you use to facilitate learning these competencies?
4 What practices should sustainable product design instructors acquire?
5 What are the challenges you face for teaching the way you do?
6 What can program directors do to support instructors in acquiring these teaching practices?

The responses to each question from the six participants were collated, first as individual cases, then clustered together using thematic analysis and discussed (results and discussion section). The responses from each participant were based on their personal experiences from instructional didactic teaching and/or Socratic supervision methods in the sustainable product design-related programs shown in Table 1.

Results and Discussion

The key findings from the case studies are summarized and detailed in this section. We organized our analysis and discussion of each case around five themes:

i Knowledge and skills of future sustainable product designers;
ii Methods, tools, and topics used to teach sustainable product designers;
iii Practices sustainable product design educators should acquire;

iv Challenges of teaching sustainable product design; and
v How can program directors help sustainable product design educators teach sustainable product design?

Knowledge and Skills Required by Sustainable Product Designers

The knowledge and skills required by product designers can be classified into two main groups (Table 2): generic knowledge and skills applicable to the design discipline, and specific knowledge and skills required in relation to sustainable product design.

The generic knowledge and skills requirements are common core content and are typically applicable to any design-based program. The second section represents knowledge and skills unique to sustainable product design. These skills require specific, often extensive (technical) knowledge and abilities that is to be acquired during a course, demanding greater time allocation within the curriculum. Some of the additional knowledge and skills also require design students to have a more technical, broader mindset or background, because they require that the designer masters new technical concepts/methods from environmental science, design engineering, and business disciplines. This led the authors to assume that the Bachelor of Science and Bachelor of Engineering Design courses, and their students, might be more suited to sustainable product design education than less technically/science-oriented product design courses.

Generic Knowledge and Skills

Communication skills are considered vitally important, not only to exchange information with other team members or tutors but also to convince or make a case for the adoption of their ideas/designs to business management.

> "Communication skills are important, both for external communication to sell ideas to executives or customers and for interpersonal communication to build high-performing teams." — Respondent 4

> "Communication skills (oral, written) are necessary for any discipline, but even more so for sustainable product designers, who will have to convince wary businesses to commercialize sustainable (high-risk, unproven) products, which often implies compromises and changes in the way an industry works." — Respondent 2

Independent lifelong learning and self-management were also considered important since such skills are becoming crucial in the digital age, given students' instant access to a wide range of online material. Enabling students to learn independently and helping them develop skills that will be useful throughout their lives through continuous professional development to ensure ongoing employment in a fast-changing world.

> "Students need to adopt a flexible approach to design, with boundaries between design disciplines such as product design, graphic design, and user experience design becoming increasingly blurred due to increasing digitalization. In the future, students will need to traverse such boundaries more seamlessly to produce sustainable solutions of value. A willingness and ability to do so will drive

Table 2 **Knowledge and skills required by sustainable product designers: General knowledge and skills are highlighted in grey and specific knowledge and skills are highlighted in white.**

	Knowledge and Skills	NTU	Cranfield	Dartmouth	DTU	TU Delft	UNSW
Generic Skills	Communication — visual & verbal, CAD sketching, modelling, presentation skills	•		•	•	•	•
	Commitment to lifelong learning	•	•		•	•	
	Critical thinking	•	•	•	•	•	•
	Problem solving	•	•	•	•	•	•
	Management — time, project, and self	•	•	•	•	•	
	Materials and manufacturing processes	•		•	•	•	•
	Teamwork	•	•	•		•	
	Negotiation		•				
	Product costing	•	•			•	
	Collaboration — group, team, or multidisciplinary	•	•	•		•	•
	Risk taking		•				
	Creativity	•	•	•	•	•	•
	Modelling or simulation skills	•	•		•	•	
	Empathic user-focused understanding & observation (user-centered design)	•	•		•	•	
	Design, development, prototyping, and testing of solutions	•	•		•	•	•
	Interdisciplinary design across subdomains	•	•		•	•	•
	Engineering-related knowledge of how the product functions	•	•		•	•	
	Failure mode and effects analysis (FMEA) and maintenance methods	•	•		•	•	
	Decision making and trade-offs in design processes	•	•	•	•	•	
Sustainable Product Design — Specific	Methods and tools to assess environmental impact: life cycle analysis (LCA), checklists	•	•	•	•	•	
	Eco-design/sustainable product design strategies and application	•	•	•	•	•	•
	Design of product-service systems (PSS)	•	•	•	•	•	•
	Sustainable/circular business models		•	•	•	•	•
	Systems thinking	•	•	•	•	•	•
	Knowledge on sustainability and circular economy	•	•	•	•	•	•
	Life cycle design	•	•	•	•	•	•
	Sustainable product design methods/ process	•	•	•	•	•	•
	Holistic understanding of sustainability including social aspects	•	•	•	•	•	•
	Reverse logistics & logistics — supply chain, manufacturing, repair		•			•	
	Dematerialization, design/component simplification	•	•		•	•	
	Product teardown and sustainable product redesign	•	•		•	•	
	Design of digital circular logistics systems		•			•	

innovation and help to speed up dematerialization. However, failure to embrace this fluidity will perpetuate the current insistence on unsustainable models of product ownership and material-based product outcomes, and may result in a lack of employment opportunities for students."—Respondent 1

Traditional design engineering methods such as FEA (finite element analysis) and FMEA (failure modes effect analysis) are also useful for the design, validation, optimization, and simulation of products to ensure that they are durable and use the optimal amount of material. Such techniques can blend with sustainable product design requirements to adhere to resource (material) efficiency and design for durability principles. The rise in the integration of digital technologies also has implications for the circular economy, so there is also a need to teach how new digital technologies—such as digital passports, which track a product's life cycle and provide product-related data—can be used to support sustainable and circular product solutions.

Specific Knowledge and Skills

Knowledge regarding sustainable product design strategies and the most appropriate ones to select and apply for individual design situations was universally identified as a key skill. With a range of specific strategies being noted, including dematerialization, sustainable material selection, design for end of life, design for repair/reuse/remanufacture/recycling, circular design, design simplification, biomimicry, design for sustainable behavior change,[18] and design for durability, which were confirmed by an earlier study.[19]

"Students should design appropriately for end-of-life destinations in line with circular economy considerations, for example, specifying materials depending on the length of use of the product … permitting short-lived products to be biodegradable and low in embodied energy, while designing in the potential for high embodied energy products to have extended lives through upgradability."—Respondent 1

The importance of not only being aware of sustainable product design strategies but of knowing how to select and apply the most suitable depending on the design problem was also emphasized.

"Broad understandings of sustainable product design strategies—strategies for enhancing the sustainability performance of a product, at a design level—are important for students. It is important that they learn how to select the most suitable strategies, according to the sustainability profile of the product under development."—Respondent 5

Knowledge about sustainability and the circular economy are important if product designers want to understand how their design decisions may affect natural and social environments. Product designers need a basic understanding of how these environments (i.e., systems) work, and how the introduction of new products may affect their functioning and balance. This introduces great complexity to sustainable product design education, requiring an extensive range of topics to be introduced that are not included in traditional design education.

18 Tracy Bhamra, Debra Lilley, and Tang Tang, "Design for Sustainable Behaviour: Using Products to Change Consumer Behaviour," *The Design Journal* 14, no. 4 (2011): 427–45, DOI: https://doi.org/10.2752/175630611X13091688930453.

19 Jeremy Faludi and Cindy Gilbert, "Best Practices for Teaching Green Invention: Interviews on Design, Engineering, and Business Education," *Journal of Cleaner Production* 234 (October 2019): 1246–61, DOI: https://doi.org/10.1016/j.jclepro.2019.06.246.

> "The students must understand the overall concept of sustainability (the social, economic and environmental dimensions) and how it has been operationalized in industry over the last 30+ years (from passive approaches and cleaner production to eco-design and sustainable design)."—Respondent 5

The ability to be able to develop a sustainable business model was noted as a core skill for future students. This is important because sustainable design solutions will be adopted by industry only if students can integrate them within a business model—otherwise, their designs risk being dismissed by industry.

> "Despite a high sustainability awareness in all spheres of society (including civil society, NGOs, public and private sector), sustainable design will not be successful and broadly implemented if there is no business case for its implementation. The students should have the skills to both calculate and sell the business case for sustainable design."—Respondent 5

The design of product-service-systems (PSS) was also seen as an important skill for students to master. Sustainable solutions, which create services instead of, or in conjunction with products, are becoming commonplace. This shift has several potential benefits. It may

i Help to dematerialize products
ii Facilitate the recovery of the product at the end of life
iii Facilitate maintenance and upgrade of the product
iv Incentivize renting/leasing a product/service instead of buying it (versus ownership).

Because of the potential environmentally-related benefits, sustainable product designers should become increasingly familiar with designing PSS. According to one respondent, this means

> "Developing integrated systems, services, and business models that connect users (businesses and consumers), products and data in more cost effective, resource productive ways; and transforming current models of ownership and consumption."—Respondent 3

A systems thinking approach was also recognized as an important skill for sustainable product designers. Sustainability is a complex issue that requires an understanding of systems complexity and the relationships involved. It is important to help students understand that any design decision—selecting a specific coating, say—during the process will ultimately exert positive and negative effects on the broader system. This is why sustainable product design students need to be experts in their subject discipline while at the same time having a broad understanding of other disciplines such as systems thinking and industrial ecology. This is often described as T-shaped education, where students have in-depth expertise in one area, while having a general breadth of knowledge of a range of other disciplines in an interdisciplinary manner.[20] While T-shaped education is important in any design discipline, it is essential in sustainable product design, which requires designers to demonstrate comprehensive, sound knowledge on relevant social and environmental issues and their assessment.

20 Denis L. Johnston, "Scientists Become Managers: The 'T'-Shaped Man," *IEEE Engineering Management Review* 6, no. 3 (1978): 67–68, DOI: https://doi.org/10.1109/EMR.1978.4306682; Mariaaluisa Saviano et al, "The Contribution of Systems and Service Research to Rethinking Higher Education Programs: A T-Shaped Model," *Sinergie Italian Journal of Management* 35, no. 104 (2017): 51–70, DOI: https://doi.org/10.7433/s104.2017.03.

> "Knowledge about systems thinking allows designers to have a holistic view of how every design decision may affect larger systems (it shows them that everything is interdependent). Sustainable issues involve large systems, which are interrelated, so it is important to understand how the designed products may affect those systems."—Respondent 2

Life cycle design is another essential skill, and one related to systems thinking. It asks designers to consider the entire product life cycle—stages include materials extraction, manufacturing, distribution, product use, and end of life—during the design phase. This is because the total impact of a product is the accumulation of the impact in each of its life cycle stages as noted:

> "It is key that the students understand the different life cycle phases and get a clear understanding that design decisions in one phase can have an impact (both positive and negative) in other phases. A systems perspective is required when doing sustainable design."—Respondent 5

The circular economy (CE) aims to decouple value creation from resource consumption. In traditional linear economic models, products are manufactured, used, and disposed of, thus losing the value of the resources contained in the products after they are discarded. In a circular economic model, products are manufactured, used, repaired, reused, refurbished, remanufactured, and recycled—to conserve the resources used (and value generated) by the product for as long as possible. Knowledge of CE principles and available CE product design strategies are necessary for students to be able to design circular products.

Methods and tools to assess the environmental and social impact (such as LCA[21] software) of product design solutions were widely recognized as a required skill for sustainable product designers. But in order to effectively use such tools, an understanding of materials, manufacturing, use phase considerations, and logistics (such as reverse logistics) is required to ensure informed and accurate decisions, as earlier studies have confirmed.[22] This also highlights the importance of understanding the functional unit when making direct comparisons in LCA software to compare the environmental impact of product or design feature options. Using the same functional unit ensures that both products will be compared objectively—apples with apples, in other words. The demand for comprehensive knowledge and skills from sustainable product designers means that teaching isn't straightforward or discipline specific.[23] Teachers must invest significant time if they are to familiarize themselves with new knowledge and tools. To teach this material requires prior learning that teachers must undertake on behalf of their students.

Sustainable product design is a complex practice. It requires that students cultivate elasticity in their thinking and learn to be comfortable with non-absolutes, hold key principles in tension with one another, and recognize the trade-offs between design decisions that may perhaps conflict with their traditional design training. The design process always involves making conflicting design decisions—one design decision may satisfy one specification (lightweight, for example), but conflict with another specification (reduced durability). In sustainable product design, this situation is even more

21 Tobias Viere et al, "Teaching Life Cycle Assessment in Higher Education," *The International Journal of Life Cycle Assessment* 26, no. 3 (2021): 511–27, DOI: https://doi.org/10.1007/s11367-020-01844-3.

22 Irel Carolina De los Rios and Fiona J. S. Charnley, "Skills and Capabilities for a Sustainable and Circular Economy: The Changing Role of Design," *Journal of Cleaner Production* 160 (2017): 109–22, DOI: https://doi.org/10.1016/j.jclepro.2016.10.130.

23 Viere et al, "Teaching Life Cycle Assessment."

common, since there are additional (sustainability-related) design requirements in the product specifications and added complexity within the field of sustainability itself. Students must learn to recognize and manage these additional and sometimes contradictory sustainable design requirements. Making design decisions in contexts that are increasingly uncertain. In addition, the use of additional tools (such as LCA) and methods to assess the sustainability of design options during different stages of the process can also complicate the design process, making it less agile and more rigid.

Other important knowledge and skills for students relate to the social impact dimension of sustainable product design[24]—including the domains of social justice and fair working conditions, among other issues. These relate more broadly to the SDGs[25] and involve wider, less clearly defined issues, thus benefitting from more exploratory forms of learning.[26] Such issues are typically addressed through projects that focus on the needs of marginalized communities, through real-world briefs and competitions in partnership with charities and NGO's, who often provide realistic and immersive project-centered resources; a good example is the Engineering for People design challenge hosted by Engineers Without Borders.[27]

Methods, Tools, and Topics Used to Teach Sustainable Product Designers

The methods and tools used to teach sustainable product designers can be generic,[28] applicable to any design discipline in higher education (grey cells, Table 3), as well as specific to sustainable product design education (white cells, Table 3).

Project-based learning is the most common teaching method within the product design and design engineering disciplines, permitting the development and reinforcement of multiple skills at the same time through practice. It can be further enhanced by focusing on live briefs increasing the learning curve and outcomes further, through giving the students opportunities to work on real-life projects simulating real-life industry work.[29] As one participant mentioned,

> "The most ideal teaching method is project-based learning in interdisciplinary teams, partnering with a manufacturer or other external stakeholder (government, non-profit or local community group). It not only gives the students experience with real-world constraints and priorities, but even more importantly, the students educate the company representatives. This is important because even if students have perfect sustainability skills and graduate today, it will be years before they are in positions powerful enough to apply those skills. We also need to educate those managing product development today, who will never go back to school, and partnering student groups with manufacturers is one way to do this."—Respondent 4

Videos and online material were also considered important. Video-based resources have great potential to elicit deep learning and enhance students understanding of the complexity of sustainability as noted in the literature.[30] Digital resources foster greater flexibility and a variety of learning formats and environments, including flipped and blended learning to permit students learning and development outside of the traditional classroom activities (at

24 Matthew Watkins, "Defining the Social Dimension of Sustainability in Product Design," *Key Engineering Materials* 572, no. 1 (2014): 24–27, DOI: https://doi.org/10.4028/www.scientific.net/KEM.572.24; Mariano Ramirez, "Designing with a Social Conscience: An Emerging Area in Industrial Design Education and Practice," in *DS68-5: Proceedings of the 18th International Conference on Engineering Design (ICED11)*, Vol. 5: *Design for X / Design to X* (Copenhagen: The Design Society, 2011), 39–48, https://www.designsociety.org/publication/30577/; Gavin Melles, Ian de Vere, and Vanja Misic, "Socially Responsible Design: Thinking beyond the Triple Bottom Line to Socially Responsive and Sustainable Product Design," *CoDesign* 7, no. 3-4 (2011): 143–54, DOI: https://doi.org/10.1080/15710882.2011.630473.

25 Yekta Bakırlıoğlu and Muireann McMahon, "Co-Learning for Sustainable Design: The Case of a Circular Design Collaborative Project in Ireland," *Journal of Cleaner Production* 279 (January 2021): 1–11, DOI: https://doi.org/10.1016/j.jclepro.2020.123474.

26 Matthew Watkins, "Fostering Deep Learning and Critical Thinking Amongst Net Generation Learners," in *Contemporary Research in Technology Education*, ed. P John Williams and David Barlex (Singapore: Springer, 2017), 23–37. DOI: https://doi.org/10.1007/978-981-10-2819-9_3.

27 https://www.ewb-uk.org/upskill/design-challenges/engineering-for-people-design-challenge.

28 D. C. A. Pigosso, T. C. McAloone, and H. Rozenfeld, "Systematization of Best Practices for Ecodesign Implementation," in *DS 77 Proceedings of the DESIGN 2014 13th International Design Conference*, ed. Marjanović Dorian et al. (Dubrovnik, Croatia: The Design Society, 2014), 1651–62, https://www.designsociety.org/publication/35308/.

29 Bakırlıoğlu and McMahon, "Co-learning for Sustainable Design," 1–11.

30 Matthew Alan Watkins, "An Audio-Visual Approach to Teaching the Social Aspects of Sustainable Product Design," *Form Academic: Forskningstidsskrift for Design Og Designdidaktikk* 8, no. 1 (2015): 1–13, DOI: https://doi.org/10.7577/formakademisk.1402.

Table 3 **Methods and tools used to teach sustainable product designers.**

	Methods, Tools, Topics	NTU	Cranfield	Dartmouth	DTU	TU Delft	UNSW
Generic Skills	Project-based learning	•	•	•	•	•	•
	Videos	•	•	•	•	•	•
	Online material	•	•	•	•	•	•
	Seminars	•	•		•	•	•
	Reading lists	•	•	•	•	•	•
	Lectures	•	•	•	•	•	•
	Flipped classroom and blended learning	•	•	•	•	•	•
	Tutorials	•	•	•	•	•	•
	Case studies	•	•		•	•	•
	Student presentations	•	•	•	•	•	•
	Workshops		•	•	•	•	•
	Constructivist approach	•	•	•		•	
	Industrial visits	•	•			•	•
	Design and prototyping of 3D solutions	•			•	•	•
	Failure modes and effects analysis (FMEA)	•			•	•	
Sustainable Product Design — Specific	Design and prototyping of PSS solutions	•			•	•	•
	Tools/methods to assess the environmental impact of products (e.g., LCA, Sustainable Minds, Ecolizer, SimaPro)	•		•	•	•	
	Eco-design and sustainable product design strategies and how to apply them	•	•	•	•	•	•
	Circular design (methods and indicators)	•	•	•	•	•	•
	Historical context of sustainability and/or circular economy	•	•	•	•	•	
	Sustainable/circular business models		•	•	•	•	•
	Techniques/technologies that can enable circular economy	•	•	•	•	•	•

their own pace) and encourage discussion and facilitate group work. As one participant mentioned, the flipped classroom offers many benefits, because it allows staff to

> "Give formative feedback to students not just about their understanding of the topic but also about their research skills, their self-management, their negotiation of the topic, their independent enquiry, their ability to be self-critical, and their perception of the system perspective to the topic." — Respondent 3

Seminars are also used frequently for teaching, with the format permitting the presentation and interactive discussion of a topic, improving students' retention of knowledge, and cultivating their critical thinking skills. As one participant mentioned,

> "Debate and discussion are often good techniques to exercise students critical thinking and argumentation skills, both of which are key professional skills required of sustainable product designers." — Respondent 5

Industrial case studies,[31] although mentioned less often, are also used to show how sustainable solutions have been implemented in real-life situations by industry.

> "[We use] industrial case studies, where students can see examples of the implementation in real-life of sustainable solutions/designs. After the presentation, the benefits, and challenges (lessons learned) of the project are discussed."—Respondent 2

Although many of the teaching methods and techniques mentioned (e.g., seminars, workshops, flipped classrooms, lectures) are commonly used in traditional design programs (not focused on sustainability), the topics/content of the methods and techniques mentioned here are focused specifically on enabling the learning of sustainable product design-related topics.

Teaching related to sustainable product design can be typically grouped into 3 main categories:

i Eco-design and sustainable product design tools/methods used to assess the circularity and environmental and social impact, and to drive design improvements, or compare solutions/design options.
ii Eco/sustainable/circular product design strategies to design solutions with low environmental-social impact.
iii General knowledge about sustainability-related topics.

The first category of tools and methods centers on the assessments of specific products or comparison between design options for the same product. This includes tools such as life cycle assessment (LCA) software-based tools[32] (e.g., SimaPro,[33] Sphera Gabi,[34] SolidWorks Sustainability,[35] or Sustainable Minds.)[36] These may also come in the form of material selection tools (Ansys Granta EduPack,[37] for example), other non-software-based tools (OVAM Ecolizer 2.0 tables;[38] VentureWell Tools for Design and Sustainability),[39] and various checklists.

The second category includes sustainable product design strategies such as design for disassembly, design for repair, dematerialization, design for longevity, design for upgrade, design for reuse, design for recycling, circular product design,[40] and design for sustainable behavior approaches.

The third category involves teaching specific knowledge and background information about topics related to sustainability like the circular economy, systems thinking, social justice, and ecology.

Some topics are taught less frequently, depending on the program type and level. These include: sustainable business models; tools and technologies to enable the circular economy; skills such as design and prototyping of PSS solutions; and modelling and simulation techniques, sometimes including finite element analysis.

Practices Sustainable Product Design Educators Should Acquire

There are two types of practices that sustainable product design educators must learn and develop: those used by every higher design educator in general (grey cells, Table 4), and those specific to sustainable product design educators (white cells, Table 4).

31 Viere et al, "Teaching Life Cycle Assessment," 518–20.
32 Ibid., 521.
33 https://simapro.com.
34 Sphera, "Gabi," 2021, https://gabi.sphera.com/software/gabi-universities.
35 https://www.solidworks.com/solutions/what-life-cycle-assessment-lca.
36 Sustainable Minds, "Eco-Concept + LCA Software," 2021, http://www.sustainableminds.com/software.
37 https://www.ansys.com/en-gb/products/materials/granta-edupack.
38 OVAM, "Ecolizer-2.0," 2012, https://venturewell.org/wp-content/uploads/Ecolizer-2.0-LCA-tables-printable.pdf.
39 https://venturewell.org/tools_for_design/introduction/.
40 Ana Mestre and Tim Cooper, "Circular Product Design. A Multiple Loops Life Cycle Design Approach for the Circular Economy," *The Design Journal* 20, sup. 1 (2017): S1620–35, DOI: https://doi.org/10.1080/14606925.2017.1352686.

Table 4 **Practices sustainable product design educators should acquire.**

	Practices	NTU	Cranfield	Dartmouth	DTU	TU Delft	UNSW
Generic	Encourage good communication between teachers and learners	•	•	•	•	•	•
	Industrial networking to inform real-world industrial student projects	•	•	•	•	•	•
	Encourage interaction/participation among learners	•	•	•	•	•	•
Sustainable Product Design—Specific	Balance creativity (design) with environmental assessment methods (science) in their teaching	•	•	•	•	•	•
	Demonstrate an awareness of current and emerging knowledge and practice in sustainable product design	•	•	•	•	•	•
	Be active in sustainable product design research and practice	•	•	•	•	•	•
	Help students to recognize and identify genuine sustainable product design from greenwashing	•	•	•	•	•	•
	Awareness of the current complexities related to sustainability in the industry		•	•	•	•	

Generic Practices

Encouraging discussion and debate among students is particularly beneficial when addressing sustainability-related topics. The exchanges can be deeply personal for staff and students, building empathy, motivation, and interest in sustainability-related subjects.

It is important that educators establish good connections with industry so they can connect student's assignments and project briefings with real-world projects and experiences. As one academic mentioned,

> "Instructors should reach out to manufacturers (or other stakeholders) to find partners for their student teams. This requires learning to network and promote classes effectively, and also being able to manage expectations so that the partners who participate are satisfied … and educators avoid derailing student teams with expectations misaligned with class deliverables."—Respondent 4

The key professional competencies specifically related to sustainable product design that instructors must cultivate are:

i A balance between teaching creativity (design) and environmental assessment methods (science).
ii An ongoing awareness of current and emerging knowledge and practice in sustainable product design.
iii Being active in sustainable product design research practice and/or design practice.

One of the challenges in teaching sustainable product design is that students have to assess the environmental-social impact of their design decisions, through the use of specific methods and tools. The application of these

methods and tools needs to be considered carefully to ensure they do not constrain the creative design process. As one respondent noted,

> "Instructors should learn to balance the creativity of design innovation with the methodical analysis of environmental and social impacts. As part of this, they should drive students toward open-ended problems, to foster critical thinking and reflection."—Respondent 4

Educators ought to have an awareness of the current state-of-the-art of sustainable product design research and practice.[41] This can be achieved through being an active researcher and/or practitioner in sustainable product design. Educators cannot hope to provide high-quality, relevant teaching content unless they stay current with relevant work in the field.

The Challenge(s) of Teaching Sustainable Product Design

We asked the academics about the challenges they had encountered teaching sustainable product design. The responses were grouped into two categories: general design-related challenges, and challenges specific to sustainable product design.[42]

i. Challenges applicable to teaching any design-related subject

- Grading project-based modules/courses;
- Personalizing teaching and learning with limited resources;
- Finding a balance between handholding of students and self-learning to develop life-long learning skills;
- Engaging students in critical thinking within a practice module;
- Finding time to work with colleagues to analyze the curriculum, share learnings, prioritize, and organize;
- Dealing with the limits of modularity, which can lead students to only utilize or apply content within a specific module (aka "the box-in syndrome");[43]
- Keeping up to date and mastering new online teaching-learning tools; and
- Finding the right balance between theory and practice throughout the course.

ii. Challenges specific to teaching sustainable product design

- Fully integrating sustainable product design into the core curriculum as standard, not as an elective subject;
- A higher volume of content related to basic environmental literacy;
- A lack of general consensus about metrics to quantify social and environmental impacts;
- Finding sufficient time to cover the broad holistic nature of this discipline in a culture of reducing contact hours and growing pressure from other aspects of the curriculum;
- Access to enough quality data for sustainability (environmental and social impact assessment) calculations;
- A lack of open-access databases to carry out environmental-social impact assessments;
- A need for more prescriptive resources to teach sustainable/circular business models;

41 Thomas Østergaard, "Decoding Sustainable Competencies and Didactics in Design Education," in *DS104: Proceedings of the 22nd International Conference on Engineering and Product Design Education (E&PDE 2020)*, ed. Lyndon Buck, Erik Bohemia, and Hilary Grierson (Herning: The Design Society, 2020), 1–6, DOI: https://doi.org/10.35199/EPDE.2020.2.

42 These have not been grouped by institutional case study to protect the respondents and institutions involved.

43 Mariano Ramirez, "Sustainability in the Education of Industrial Designers: The Case for Australia," *International Journal of Sustainability in Higher Education* 7, no. 2 (2006): 189–202, DOI: https://doi.org/10.1108/14676370610655959.

- A focus on teaching limited aspects of the discipline (such as material selection only), rather than taking a holistic approach;
- The lack of an informed, general appreciation for sustainable product design within the broader discipline of design;
- Handling misconceptions about what sustainable product design and design for the circular economy are within a discipline-specific context at an institutional level; and
- Obtaining the resources and support to find industrial partners who want to collaborate in sustainable product design projects

Assessment is more challenging because projects have to be assessed on additional criteria (environmental-social impact), which is typically difficult to do with accuracy. Due to the shorter timeframes involved and lack of manufacturing development, there is often insufficient information or data to carry out an accurate or complete environmental-social impact assessment of students' products or project proposals, which can mean that is difficult for the teacher to evaluate or grade the environmental-social impact claims in the students' projects. Additionally, there is a lack of consensus about social (and to some degree environmental) harmonized metrics and standards used for assessment and comparisons. There are too few extensive, reliable databases to inform LCAs (detailed and simplified), meaning that assumptions have to be made, impacting on the reliability of the results. This can make assessment of a product's potential environmental and social performance challenging.

Simplified LCAs are often used in an educational setting, where full detailed LCAs are too complex and time-consuming to be used within students' projects short time frames. Furthermore, students' projects do not provide enough information to carry out a complete LCA, since there are no manufactured outcomes in undergraduate and postgraduate project work. Simplified tools, however, are less accurate and can provide misleading results, so more user friendly, complete, and accurate tools are needed. In addition, educators must have specialist knowledge about impact assessments to be able to determine whether students have used the software correctly and accurately. Assessing whether inputs and outputs, used in the assessments, are accurate can take a considerable amount of time and expertise—without the requisite expertise, educators will not be able to assess the work fully. Therefore, it is important to recruit staff that are specialists in sustainable product design or provide training and opportunities for staff to develop the required skills to permit accurate assessments.

Respondents pointed out some other key challenges.

> "I think that the biggest challenge with project-based courses is grading, both in relation to different group members, and to the trade-off between evaluating the learning process and the outcome."—Respondent 5

> "Project-based learning is extremely time-intensive to grade, especially LCAs of new products and new design ideas for products. It is hard to foist this duty onto Teaching Assistants/Associate Lecturers, because grading of LCAs requires technical knowledge of manufacturing and materials as well as environmental impacts on top of attention to detail and critical thinking."—Respondent 4

One key challenge noted was the lack of integration of sustainable issues as a core component of product design programs. This restricts the time allocation within the curriculum for dedicated sustainable product design issues, which can result in incomplete education focused on single issues. Mere material-selection exercises make it difficult to properly teach or cover this complex and comprehensive subject, for example, and providing sustainable product design courses as electives runs the risk of students adopting box-in syndrome,[44] only applying their sustainability teaching during the sustainability module and not thereafter in their other studies.

In addition to this, there is a growing need for readily accessible teaching material—sustainable business models, open-access LCA databases, case studies about sustainable product implementations, and environmental literacy, to better inform teaching.

How Can Program Directors Help SPD Educators Teach Sustainable Product Design?

The ideal opportunities for investment or development we have identified are below, followed by a discussion of some practical applications.

- Invest in developing or redeveloping classes, or support research or other learning activities for staff to develop sustainable product design knowledge and resources.
- Promote the demand for sustainability skills in graduates in industry.
- Enhance faculty or institutional focus on sustainability issues within the product design curriculum.
- Encourage visits to recycling centers for real-world perspectives.
- Involve academic staff and students in campus wide sustainability initiatives and strategic sustainability plans of the university such as greening the campus facilities, procurement, and operations.
- Encourage educators to attend conferences and training programs, and to network with other academics and practitioners working in sustainable product design, to improve their practice mutually and increase and update their knowledge.
- Allow greater flexibility in the teaching of the curriculum.
- Encourage holistic, multidisciplinary design approaches and outcomes where relevant, to prevent a focus on single issue outcomes—by limiting a sustainable design project to a material-based product outcome can be too restrictive and retrograde, for example.

Crucial to the integration of sustainable product design knowledge and practice in HE is high-level endorsement (in the form of resources) from heads of schools/departments to facilitate the adoption and promotion of sustainable product design education courses into the standard design curriculum. Earlier research has also pointed to the need to integrate sustainability issues in design-based curricula.[45] Nevertheless, it is still a problem that needs to be addressed. It is necessary to provide the knowledge and skills, and incentives, to product design educators unaware of (or unwilling to adopt) sustainable product design principles, methods, and tools, so they can upgrade their knowledge and inform their teaching practice. It is

44 Ramirez, "Sustainability in the Education," 195.

45 Matthew Alan Watkins and Vicky Lofthouse, "A Review of Sustainability within Product and Industrial Design Courses in British Universities," in *DS62: Proceedings of E&PDE 2010, the 12th International Conference on Engineering and Product Design Education*, ed. Casper Boks et al. (Trondheim: Institute of Engineering Designers, 2010), 346–51, https://www.designsociety.org/publication/30177/; Mariano Ramirez, "Promoting Sustainability through Industrial Design Studio Projects," in *Proceedings of Connected 2007 International Conference on Design Education*, ed. Robert Zehner and Carl Reidsema (Sydney: University of New South Wales, 2007), 1–5, available at http://unsworks.unsw.edu.au/fapi/datastream/unsworks:399/SOURCE1.

also important to promote the discipline among students and industry (via university marketing) to inform them about the benefits for companies and society.

To increase the knowledge of sustainable and non-sustainable product design educators, heads of departments could encourage (and support) attendance at sustainable product design events — conferences, seminars, exhibitions — and visits to companies involved with sustainability.

Some potential solutions to these issues were suggested by one respondent.

> "The lack of knowledge can be solved by sending faculty to train-the-trainer classes in sustainability, providing online repositories of curated curricula, and building networks for faculty to support each other. A lack of perceived business demand can be solved by partnering with companies on projects; if the companies pay to participate, this can also help solve the lack of funding and lack of interest by other faculty." — Respondent 4

Flexibility within the curriculum is also key; permitting students to explore non-physical solutions to design problems (such as PSS) can be disruptive. It stretches the boundaries of the product design discipline often through dematerialization, diverging into new territory such as new combinations of products and services, but is an important aspect of fostering design thinking approaches for sustainable solutions that also prepares students more effectively for breadth in their future careers.

Limitations of This Study

First, this research was conducted, analyzed, and largely written prior to the Covid-19 pandemic and should be read and understood accordingly, outside of the restrictions and subsequent significant online developments in teaching and learning in HE globally.

One of the key potential limitations of this study is in the number of case studies considered. While all the academic respondents had broad and significant expertise in sustainable product design and research, the study represents only six institutions from five countries. Further studies on this topic should obtain responses from a larger number of case studies, from a greater geographical region to validate and build on these results. A larger sample would allow pattern identification (common answers among participants), and reveal possible distinct geographical variances. Furthermore, the countries represented typify a predominantly Western, Eurocentric model of education and design, and future research could benefit from a wider geographical sample.

Another limitation is that the responses may have not captured the full spectrum of teaching practices at each institution, since key knowledge may have been accidentally omitted or implied, and the responses noted don't make up the entirety of product design or design engineering provision in these institutions. Other academics within the same institution may have alternative or additional perspectives. Each respondent was given the opportunity to review this article, however, and add additional missing information, particularly in relation to the content presented in Tables 2–4. The review

enabled them to recognize aspects from other respondents that they may have forgotten to include from their own experience initially. Furthermore, a large survey based on a closed-ended questionnaire could be developed focusing on the study of the key issues or topics identified in the initial findings of this qualitative multiple case study, to confirm or refute the findings.

Conclusion

This article has discussed current practice in sustainable product design education from six academics working in six universities across five countries, with experience in education and research in this area. The key insights reveal that sustainable product design education and teaching requires additional knowledge and skills related to sustainability, beyond the typical knowledge and skills sets expected of traditional product designers. These additional skills include being able to select and use methods and tools to assess the social and environmental impact of the design decisions they make, having an understanding of sustainability and circular economy issues, and familiarity with life cycle design. We also point out that students need a sound understanding of systems thinking, which requires greater critical thinking and handling of complexity than typically required in traditional product design practice. Finally, we found that a deeper understanding of sustainable or circular business models is needed so that students know how to make a business case for sustainable products. Sustainable product design educators should master the above mentioned knowledge and skills in order to be able to teach them to students, who will become the sustainable product designers of the future. But for this to happen, those in leadership at universities, schools, and departments, where product design educators work, must recognize the importance of this discipline and fully support its full integration into the curriculum, not as an elective course, but as an integral part of the program. This would enable them to dedicate the resources required to deliver this complex subject fully and comprehensively. It would also ensure that all product design students are trained appropriately, and enable all product design educators to upgrade their knowledge and skills to be able to teach and assess this subject, thus increasing literacy and expertise in this area, which would improve the quality of sustainable product design education overall.

Declaration of Interests

There are no conflicts of interest involved in this article.

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Appendix. Additional Supporting Resources List

The following list of resources has been provided as recommend further study for those wishing to increase their knowledge in sustainable product design. It is by no means exhaustive but it is an extensive summary of key sources as used and recommended by the authors.

Books/Texts on Design for Sustainability in General:

Ashby, Michael F. *Materials and the Environment: Eco-informed Material Choice*, 3rd ed. Oxford: Butterworth-Heinemann, 2021.

Benyus, Janine M. *Biomimicry: Innovation Inspired by Nature.* New York: HarperCollins, 1997.

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Ceschin, Fabrizio, and İdil Gaziulusoy. *Design for Sustainability: A Multi-level Framework from Products to Socio-technical Systems*. Abingdon: Routledge, 2019.

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Charter, Martin, and Ursula Tischner. *Sustainable Solutions: Developing Products and Services for the Future*. Abingdon: Routledge, 2001.

Chick, Anne, and Paul Micklethwaite. *Design for Sustainable Change: How Design and Designers Can Drive the Sustainability Agenda*. Lausanne, Switzerland: AVA, 2011.

Egenhoefer, Rachel Beth, ed. *Routledge Handbook of Sustainable Design*. Abingdon: Taylor & Francis, 2017.

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Kärnä, Anna. *Environmentally Oriented Product Design: A Guide for Companies in the Electrical and Electronics Industry*, 2nd ed. Helsinki: Federation of Finnish Electrical and Electronic Industry, 2002.

Kurk, Fran, and Curt McNamara. *Better by Design: An Innovation Guide: Using Natural Design Solutions*. St Paul, MN: Minnesota Pollution Control Agency. https://www.pca.state.mn.us/sites/default/files/betterbydesign.pdf.

Lewis, Helen, and John Gertsakis. *Design + Environment: A Global Guide for Designing Greener Goods*. Sheffield: Greenleaf, 2001.

McAlonee, Tim, and Niki Bey. *Environmental Improvement through Product Development:* A Guide. Copenhagen: Danish Environmental Protection Agency, 2009. https://backend.orbit.dtu.dk/ws/portalfiles/portal/3996106/.

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Niederrer, Kristina, Stephen Clune, Geke Ludden, eds. *Design for Behaviour Change: Theories and Practices of Designing for Change*. Abingdon: Routledge, 2018.

Niemann, Jörg, Serge Tichkiewitch, and Engelbert Westkämper. *Design of Sustainable Product Life Cycles*. Berlin: Springer, 2009.

Penty, Jane. *Product Design and Sustainability: Strategies, Tools and Practice*. New York: Routledge, 2020.

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Stibbe, Arran, ed. *The Handbook of Sustainable Literacy: Skills for a Changing World*. Totnes: Green Books, 2009.
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United Nations. "Sustainable Development Goals (SDGs)." https://sdgs.un.org/goals.

Books/Texts on Design for Circular Economy:

Bakker, Conny, Marcel den Hollander, Ed van Hinte, and Yvo Zijlstra. *Products that Last: Product Design for Circular Business Models*. Delft: Technical University of Delft, 2014.
Charter, Martin. *Designing for the Circular Economy*. Abingdon: Routledge, 2018
Cooper, Tim, ed. *Longer Lasting Products: Alternatives to the Throwaway Society*. Abingdon: Routledge, 2010.
Ellen Macarthur Foundation. "Circular Consumer Electronics: An Initial Exploration." https://emf.thirdlight.com/link/uylh69ffuojx-2dt8yd/@/download/1.
Ellen Macarthur Foundation. "Reuse: Rethinking Packaging." https://emf.thirdlight.com/link/rzv910prtxn-tfiulo/@/.
Ellen Macarthur Foundation. *Upstream Innovation: A Guide to Packaging Solutions*. https://emf.thirdlight.com/link/aiqpsmx35l7n-bll86j/@/download/1.
Stahel, Walter R. *The Circular Economy: A User's Guide*. Abingdon: Routledge, 2019.

Books/Texts on Design for Social Sustainability:

Berman, David B. *Do Good Design: How Design Can Change Our World*. Berkeley: AIGA Design Press, 2009.

Crul, M. R. M., J. C. Diehl, and C. Ryan, eds. *Design for Sustainability: A Step-by-Step Approach*. Paris: United Nations Environment Programme, 2009. https://wedocs.unep.org/bitstream/handle/20.500.11822/8742/DesignforSustainability.pdf.

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Whiteley, Nigel. *Design for Society*. London: Reaktion Books, 1997.

Pictorial Books on Design for Sustainability:

Barbero, Silvia, Brunella Cozzo, Paolo Tamborrini. *Ecodesign: Eco-friendly Objects for Everyday Products*. Potsdam: Tandem Verlag, 2009.

Fuad-Luke, Alastair. *The Eco-Design Handbook: A Complete Sourcebook for the Home and Office*, 3rd ed. London: Thames & Hudson, 2009.

Pilloton, Emily, and Allan Chochinov. *Design Revolution: 100 Products That Are Changing People's Lives*. London: Thames & Hudson, 2009.

Proctor, Rebecca. *The Sustainable Design Book*. London: Laurence King, 2015.

Reis, Dalcacio, and Julius Wiedemann, eds. *Product Design in the Sustainable Era*. Köln: Taschen, 2010.

Toolkits for Design for Sustainability:

Biomimicry Institute. Ask Nature. https://asknature.org.

Circular Academy. Circular Academy Toolbox. https://www.circular.academy/toolbox.

CORPUS: SCP Knowledge Hub. Sustainable Street 2030. https://www.strategicdesignscenarios.net/sustainable-street-2030/.

Danish Design Centre. Circular Economy Toolbox. https://ddc.dk/tools/designing-your-circular-transition/.

Design School Kolding, Denmark. Sustainable Design Cards.https://sustainabledesigncards.dk/.

Ellen Macarthur Foundation + Cradle-to-Cradle Products Innovation Institute. Safe & Circular Product Redesign Workshop. https://emf.thirdlight.com/link/sud6mp69ctdd-5uxznn.

Ellen Macarthur Foundation + IDEO. The Circular Design Guide. https://www.circulardesignguide.com/.

Ellen Macarthur Foundation. Circular Economy Teaching Resources. https://ellenmacarthurfoundation.org/resources/education-and-learning/teaching-resources.

Ellen Macarthur Foundation. How We Make Stuff: Can We Do Things Differently? https://www.made2bmadeagain.org/.
Franco, Alessio. Circular Design Toolkit. https://www.circulardesign.it/.
IKEA. Circular Product Design Tool. http://circularityblueprint.ikea.net/.
Konietzko. J. Circularity Deck. https://www.circularitydeck.com/masterclass.
Learning Network on Sustainability. SDO: Sustainability Design Orienting Toolkit. http://www.lens-international.org/tools/view/3?server_id=1.
Learning Network on Sustainability. Sustainable Design Learning Tools & Resources. http://www.lens-international.org/.
Okala Team. Okala Ecodesign Strategy Wheel App. http://www.okala.net/Okala%20Ecodesign%20Strategy%20Guide%202012.pdf.
Selvefors, A. and Rexfelt, O. Use2Use Toolkit for User-Centred Circular Design. https://www.use2use.se/.
Sweeney, L. B. and Meadows, D. Systems Thinking Playbook for Climate Change: A Toolkit for Interactive Learning. Eschborn: Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH, 2011. https://klimamediathek.de/wp-content/uploads/giz2011-0588en-playbook-climate-change.pdf.
The Centre for Sustainable Design. Resources. https://cfsd.org.uk/resources/.
VentureWell. Tools for Design and Sustainability. https://venturewell.org/tools_for_design.

YouTube Modules on Design for Sustainability:

Leonard, A. The Story of Stuff Series. https://www.youtube.com/channel/UCRNnYXD8Elz5zwKQ2jAcbAg.
Dawn, D. and Faludi, J. Autodesk Sustainability Workshop. https://www.youtube.com/channel/UCsbxR4olShGq_S3sSGh0dIA.
Ellen Macarthur Foundation. The Circular Economy Show. https://www.youtube.com/channel/UCQAC2otE5_agzHZPnk3mE5w.
Sustainable Minds. Sustainable Minds Series. https://www.youtube.com/channel/UCilUdDnYwlr24-FpvVKYAkw.
ANSYS-Granta Design. Introducing the Eco Audit Tool in Ansys Granta Edupack. https://www.youtube.com/watch?v=9qlw7JroxRY.

Massive Open Online Courses on Design for Sustainability:

Boylston, S. on LinkedIn Learning. Learning Design for Sustainability. https://www.linkedin.com/learning/learning-design-for-sustainability.
TU Delft on EdX. Circular Economy: An Introduction. https://www.edx.org/course/circular-economy-an-introduction.
TU Delft on EdX. Design for Recycling of Electronics in a Circular Economy. https://www.edx.org/course/design-for-recycling-of-electronics-in-a-circular-economy.
TU Delft on EdX. Engineering Design for a Circular Economy. https://learning.edx.org/course/course-v1:DelftX+PDCE01x+2T2021.
TU Delft on EdX. Sustainable Packaging in a Circular Economy. https://www.edx.org/course/sustainable-packaging-in-a-circular-economy.
Wageningen University on EdX. Circular Economy: An Interdisciplinary Approach. https://learning.edx.org/course/course-v1:WageningenX+CE01x+2T2021.