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Making Sustainably: Embedding Sustainable Practices in Project-based Design Engineering

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Abstract

Hands-on, project-based learning is now understood to be an integral component of engineering education, particularly in design engineering courses. Although these project-based modules often focus on sustainability goals and encourage students to consider sustainability as a key factor in design solutions, the same attention may not be given to how the project is subsequently carried out. Implementing practices that encourage students to prototype and iterate designs through a process that centres sustainability can help to further embed these concepts into the learning experience.

This paper explores how academic makerspaces and workshops can be used as tools to demonstrate sustainability practices, and to reinforce sustainability-based learning outcomes of design modules. It examines the need to impart sustainable design principles by promoting thoughtful material use and waste reduction. Through a case study of an academic makerspace, consisting of documentation of existing practices and a user survey, the paper identifies challenges and opportunities for ensuring that practical project-based modules reflect the goals of sustainability education. It explores the importance of effectively managing materials and resources to instil students with an understanding of their finite nature and the need for responsible consumption.

1 Introduction

Over the past few decades, education for sustainable development (ESD) has become an increasingly central focus within engineering (Gutierrez-Bucheli et al., 2022; Thüerer et al., 2018). It is now widely recognised that future generations of engineers must be equipped with the knowledge and skills to drive social and environmental change. Much thought has been directed to the curricular integration of sustainability topics (Leifler & Dahlin, 2020), with many studies supporting the value of horizontal integration, in which sustainability is embedded across modules rather than taught as a standalone course (Watson et al., 2013). A less extensively explored area is the extent to which students are able to translate these academic lessons into their practical, hands-on work.

Academic makerspaces, which are an increasingly common feature of engineering education (Longo et al., 2017), offer students opportunities to engage in design and making projects in a self-directed and less formally supervised environment. These spaces provide a valuable lens through which to examine how students apply sustainability concepts in practice, under real-world constraints. This paper explores the role of academic makerspaces as a platform for reinforcing sustainability education through hands-on learning. It presents a case study of the King's College London Engineering Makerspace, investigating student attitudes toward sustainable design and making practices, and identifying opportunities to better align practical learning with sustainability goals.

2 Background

2.1 The role of Makerspaces in Engineering Education

Although definitions vary, the term makerspace broadly describes a shared workshop environment aimed towards prototyping and low-cost fabrication rather than manufacturing of high-end parts. While makerspaces differ significantly in a physical sense, the uniting thread is often considered to be the ‘maker mindset,’ which values experimentation, ideation, collaboration, and interdisciplinary thinking (Regalla, 2016). Within engineering education, increasing focus on project-based learning (PBL) and design thinking (Dym et al., 2005; Mills, 2003) has aligned with the growing curricular integration of makerspaces within the field (Anand et al., 2024; Taheri et al., 2019).

Makerspaces are seen to present a meaningful learning opportunity when compared to traditional engineering workshops as they are typically more accessible and safer, allowing students greater participation at lower experience levels (Youmans et al., 2018). It has further been proposed that delivering courses within a higher education makerspace can enhance the teaching of design principles by reducing the gap between theoretical learning and practical application (Wilczynski et al., 2016). This is reinforced by a case study from Portland State University, where a microwave circuit design course was reimaged to incorporate the use of the campus makerspace (Pejcinovic, 2017). The study concludes that inclusion of the makerspace enabled a shift toward hands-on practice and allowed students to fully engage with the design-build-test cycle.

One study that conducted interviews with student makerspace users found that engagement with the space supported a deeper understanding of engineering principles. The opportunities for hands-on experimentation were seen to advance skills such as learning through failure and collaboration, with students able to apply theoretical knowledge to practical design and making (Nadelson et al., 2019). This is supported by other findings examining the integration of makerspaces into engineering education, which find tangible improvement in project quality due to the introduction of makerspaces into academic courses (Anand et al., 2024; Taheri et al., 2019).

2.2 Sustainability in academic Makerspaces

The Maker movement is typically seen to align with sustainable practices, and there has been found to be a high level of awareness around environmental issues within the Maker community (Unterfrauner et al., 2019). Waste reduction practices are widely adopted within makerspaces, such as the use of scrap material, recycling of projects and components, repair workshops and soft prototyping (Honkala et al., 2023).

While such practices are indeed commonplace, the suggestion that Makerspaces are inherently sustainable overlooks day-to-day practicalities and pressures experienced in such spaces (Prendeville et al., 2017). For academic makerspaces particularly, certain challenges have emerged in the growing number of spaces operating alongside the curriculum as teaching labs.

Students and makerspace staff have cited the pressure of working to deadlines, as well as inexperience with machinery and materials as barriers to sustainable fabrication within these spaces (Honkala et al., 2023; San Juan & Murai, 2022). Furthermore, it has been identified that, where material is freely provided to students, there is some alienation between students and the cost associated with materials from both a financial and environmental standpoint (Bansal & Lechelt, 2023). In some instances, affordances that make

makerspaces accessible can also enable unsustainable behaviours. For instance, the ease and speed of computer aided manufacturing (CAM) processes such as laser cutting and additive manufacturing may discourage careful planning, leading to repeated iterations of parts and excessive material consumption (Bouwma-Gearhart et al., 2021). This intersects with the issue of inexperience, as machine operation by users unfamiliar with CAM has been found to increase resource consumption (Laverne et al., 2019).

Given the pedagogical value placed on exploration, iteration and failure in design-based education and PBL, a tension exists between this framework and the principles of waste reduction and sustainable fabrication (Lee & Manfredi, 2021). Waste is a natural by-product of the prototyping process, and efforts to reduce this within an academic environment must strive to ensure that learning outcomes for students do not suffer as a result. The sustainable operation of a makerspaces relies upon on the culture and behaviours it encourages, requiring ongoing collaborative work between makerspace staff, academic leads and student users.

2.3 Makerspaces as a space for practical sustainability learning

Many engineering modules now incorporate some element of ESD, often informed by the sustainable development goals (Hąbek et al., 2024), and engineering students have generally been found to hold positive attitudes towards sustainability (Tang, 2018)(Rosen, 2013). However, it is recognised that pro-environmental attitudes do not always correspond to behavioural outcomes in the real world (Wyss et al., 2022), and that simply providing students with a theoretical understanding of sustainable development is insufficient (Tejedor et al., 2019). Instead, interactive teaching strategies that enable students to apply their learning to their immediate environment should also be integrated into the curriculum (Ariza & Olatunde-Aiyedun, 2023; Martín-Garin et al., 2021).

This growing recognition of the importance of experiential learning experiences and PBL, concurrent with the increasing utilisation of makerspaces as a teaching resource has presented the opportunity to use making-based education to explore and apply sustainability practices (Bouwma-Gearhart et al., 2021; Reichenbach & Reynante, 2019). In recent years, several examples of curricular integration of makerspaces for sustainable development-aligned projects have been disseminated, including those from Worcester Polytechnic Institute (Anand et al., 2024) and Langara College (Taheri, 2018) both of which reported positive outcomes in the student experience.

Despite growing recognition of the potential of makerspaces to support ESD, there is little literature examining how tangible sustainability practices within makerspaces connect to sustainability content in related academic modules. This work aims to explore this question, focusing on a case study of the King's College London (KCL) Engineering Makerspace.

3 Lessons, Challenges and Student Perspectives of sustainability in a curricular-integrated makerspace

3.1 Overview of the KCL Engineering Makerspace

The KCL Engineering Makerspace is a dedicated facility designed to support PBL for undergraduate students in the Department of Engineering. It is comprised of three rooms total, as depicted in Figure 1. One hosts CAM equipment, while the other two are identical spaces containing more traditional workshop machinery, electronics benches and assorted other equipment (Figure 1 B&C). The spaces are physically

situated within classroom-style teaching spaces as shown in Figure 2. During sessions, students are able to move between the makerspace workshops and adjacent classroom.

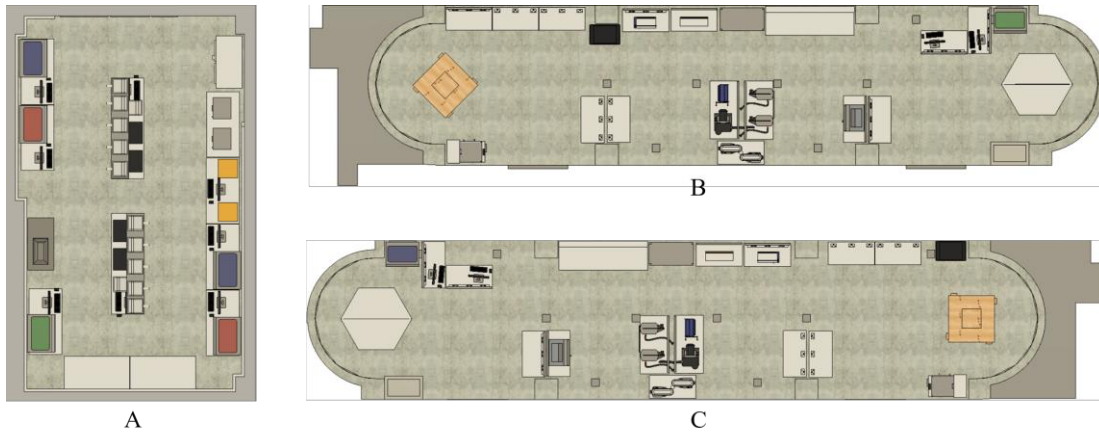


Figure 1: Layout of the KCL Engineering Makerspace comprised of A) the CAM lab, B) & C) the identical workshop spaces

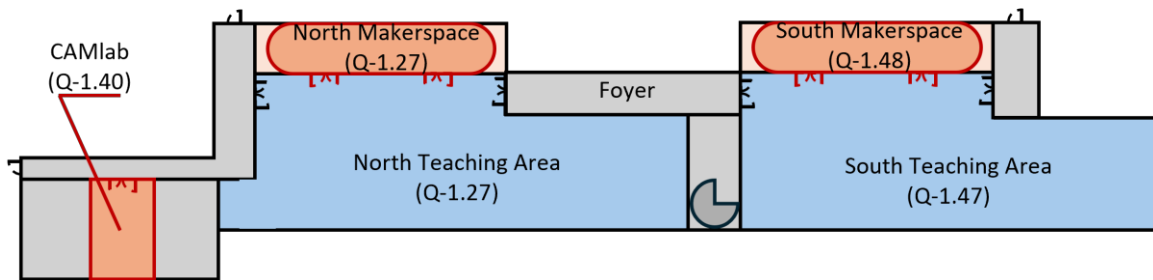


Figure 2: Placement of the makerspace rooms within the teaching space

The space aims to facilitate the production of functional prototypes and is used by 1st Year through to master's students with a wide a range of experience levels. All students and staff are required to complete an online and in-person induction prior to beginning work in the space. It is run by technical staff who also coordinate a team of makerspace assistants comprised of the undergraduate and postgraduate student body.

3.2 Educational context and curricular integration

The Department of Engineering at KCL was reestablished in 2019 after a period of closure, with newly refurbished teaching facilities including the purpose-built makerspace. The newly developed programme consciously employs a 'create-first' programme with design and make as a focal point (Ciriello & Lucas, 2023). Students undertake a major project-based design module each academic year, allowing continuous development of design and systems thinking as they progress. Sustainability is a foundation for the newly developed programme, with sustainable design and socially aware innovation being embedded into projects briefs and assessment criteria.

The makerspace is a key part of this pedagogical structure, enabling students to complete practical elements of the design modules. Students are given access to the space during timetabled sessions for each module, during which time makerspace staff are available to advise. Makerspace technical staff work closely with academics on design modules and are often involved in teaching outside of makerspace sessions. An

example of this is during ‘design reviews’ in which academics, technical staff and fellow students give feedback on designs prior to the start of the making process. Student projects are structured such that over the course of the module there are further opportunities for interactions between makerspace staff, often comprising of project milestones that must be completed and demonstrated to gain access to additional materials and resources (Palmer et al., 2024). This provides a learning environment in which students have the freedom to explore design and making methods, while still providing some structure towards the relevant learning outcomes as well as resource management.

The recent reformation of the KCL engineering programme has provided the opportunity for the makerspace to be integrated into the curriculum across many modules, an educational makerspace model distinct from providing standalone classes and workshops (Cooke et al., 2020). The space is physically integrated into adjacent teaching areas (Figure 2), allowing sessions to be run across the makerspace and classroom environment simultaneously. This model of curricular integration leads to a cooperative relationship between the curriculum and the makerspace. Equipment, material stocks and staff training are reviewed yearly based on newly created modules or alterations to existing courses, as well as the evolving direction of final year extended projects. At the same time, the capabilities of the makerspaces are a key consideration informing the design or alteration of modules.

This model means that the makerspace functions as an educational through line, rather than a purely vertical or horizontal element. Students engage with the space across multiple years and modules but also receive makerspace-specific training and learning experiences. The continuity across years provides an opportunity for reinforcement of sustainability values and offers a unique site for longitudinal educational interventions.

3.3 Established Sustainability Practices

Analysis of the currently established sustainability-focused practices in the KCL Engineering Makerspace found that they fall into 4 core categories. These were: reuse initiatives, waste disposal, reduced consumption and guidance and information. Figure 3 lays out these categories and the practices that they encompass, the majority of which are straightforward and require little clarification. Initiatives that may be more novel include the component library, coin-based consumables system and design or CAD reviews.

Design reviews or CAD reviews are sessions, often taking place outside of the makerspace itself, in which students present their designs or CAD models for review and feedback. In some instances, designs are presented only to makerspace staff, and in others makerspace staff are present as part of a wider group also comprised of academic staff and other students. These review sessions aim to encourage thoughtful design and digital prototyping prior to physical work beginning in the makerspace.

The coin system refers to a management and distribution scheme for consumables such as sheet material, electronic components and 3D printing time. An allocated number of laser cut ‘coins’ are given to students at the beginning of design projects as a consumables budget, which they manage throughout the term. The aim of this system is to encourage students to use freely available scrap materials where possible, and to reduce the overall amount of material consumed.



Figure 3: Established sustainability practices identified in the makerspace

The component library is a cart containing used components such as motors and microcontrollers that have been reclaimed from previous projects. These components are available to students either for free, or at a discounted price in relation to the coin system, to encourage reuse.

3.4 Successes, Barriers and Opportunities in Embedding Sustainability

As outlined in Section 2, academic makerspaces present a unique opportunity for embedding sustainability in engineering education as they provide a platform for reinforcing taught concepts such as lifecycle thinking, responsible material choice, and waste minimisation. Given this, it is instructive to understand to what extent students are conscious of these sustainable practices in the makerspace, and how equipped they feel in applying sustainability principles to their real-world making practices.

To explore these perspectives, an anonymous survey was distributed to students who had engaged with the makerspace as part of their PBL modules. The survey aimed to gather quantitative data on students' awareness of sustainability practices within the space, perceived barriers to sustainable prototyping, and suggestions for improvements. A total of 24 responses were collected over a period of 2 weeks, representing engineering students from across all year groups and project modules. The survey consisted of open-text prompts, allowing for thematic exploration of student responses. Responses were manually reviewed and broken into themes, with reoccurring themes identified and grouped.

3.4.1 Existing Strengths and Successful Practices

Participants were first asked to identify existing sustainability practices within the makerspaces, with results displayed in Table 1. Respondents identified sustainability practices in the makerspace along the same core themes that were recognised in Section 3.3. Most, but not all, of the specific practices previously discussed were identified. The most frequent responses were related to reuse initiatives, especially use of scrap material which was mentioned 16 times. There was also significant awareness around resource reduction, with the coin system and the availability of more sustainable materials for soft prototyping, such as recycled cardboard, both being flagged by 5 respondents. Waste disposal is the least mentioned of these themes, with only recycling bins being mentioned. Within the theme of guidance and information, interactions with

makerspace staff were most frequently cited as a positive factor, followed by encouragement towards digital and soft prototyping.

Table 1: Summary of thematic coding of participant responses to “What sustainability practices (if any) are you aware of in the makerspace?”

Theme	Sub-theme	Example quote	Response frequency
Reuse Initiatives	Use of scrap material	There are bins filled with scrap materials, be it foam or other kinds of materials. It's so we don't directly throw things away as other people might need the smaller used pieces of that same material.	16
	Component reuse	Some examples include...designated areas for reusing parts or components from previous projects	1
	Material reclamation	UpCycling, e.g. turning orange bag into a net.	3
Waste disposal	Recycling bins	Some sustainability practices I've noticed include...placing recycling bins for paper and plastic waste	3
Reduced Consumption	Sustainable prototyping	Making use of scrap parts for soft prototypes	5
	Coin system	Also the concept of using those coins to budget helps with sustainability as it requires us to be mindful of how much we are using and if our material choices are really optimal	5
	Print job viability	Designing models for 3d printing efficiently with the best orientation to reduce waste in printing materials	1
	Energy consumption	There's also some awareness around reducing energy consumption by turning off unused equipment.	3
Guidance and information	Staff interactions	...for one of my projects I asked the TAs what materials could be more sustainable to use for the design and they provided very good ideas which we did end up using in our final product	4
	Signage	Some examples include...signs encouraging responsible material usage	1
	Encouragement to prototype	There's also encouragement to use digital prototypes before physical ones.	3
	Academic incentive	The projects we work [on] put a lot of emphasis on how sustainable our final product has to be as this is the standards for most engineering products nowadays.	1

CAD reviews	We are encouraged to make prototypes from cardboard first, and also provide a good CAD before beginning to work physically.	1
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3.4.2 Barriers and Constraints to Practising Sustainability

The main barriers were classified as belonging to three themes: lack of knowledge, material usage and project constraints. Each of these were split into sub-themes, the most frequently mentioned of which were inexperience of users and time constraints within projects. Also identified as major barriers were competing priorities within the project, and a lack of access to sustainable materials, with 6 mentions apiece. Despite positive responses in Table 1 regarding guidance and information, it is clear from the responses around insufficient guidance and lack of incentives that there is still a desire for more structured pedagogical intervention relating to the application of sustainable thinking in these PBL modules.

Table 2: Summary of thematic coding of participant responses to “What barriers prevent you from practicing sustainability in your projects?”

Theme	Sub-theme	Example quote	Response frequency
Lack of knowledge	Inexperience	Design inexperience leads people to make poor decisions when designing projects, resulting in waste when it doesn't work/fit together as expected.	6
	Insufficient guidance	There's a lack of awareness or guidance on sustainable alternatives and how to implement them effectively in projects.	3
	Unclear signage	Bins not always clearly labelled	1
Material usage	Material sustainability	One major barrier is the limited availability of sustainable or recycled materials in the makerspace.	5
	Constraints of scrap material	Scrap materials which are not reusable due to inefficient use and placement of laser cutting models	4
	Limited recycling options	Lack of PLA recycling	2
Project constraints	Time pressures	Strict time constraints for making sometimes mean that sustainability is not the top priority as a sustainable approach to the project can take more time/effort without being rewarded much.	6
	Lack of incentives	Haven't been enforced by professors or taught in modules where I use the makerspace.	3
	Competing priorities	The need to make a fully functional and durable prototype. Also it is kind of embarrassing to present something that is not aesthetically pleasing so we look for better looking materials or unnecessary ways to decorate.	5

3.4.3 Opportunities for Deeper Integration

The results presented in Table 3 relate to suggestions for improving sustainability in the makerspace. Responses demonstrate an interest in increased educational support and improvements in resource management, as well as changes to project structure although to a lesser extent. Respondents indicated an appetite for more makerspace and module-based guidance, particularly in the form of learning about sustainable manufacturing. There was also interest around improving recycling options, for example by introducing 3D print recycling facilities, in which failed or unused prints are shredded and used in new plastic forming processes.

Table 3: Summary of thematic coding of participant responses to “Any other comments or suggestions for making the makerspace more sustainable?”

Theme	Sub-theme	Example quote	Response frequency
Educational support	Enhanced basic training	Talk about sustainability during the makerspace induction	5
	Dedicated workshops	I think it would be nice to have a workshop session based on material science and how to implement the knowledge we gained from this module into our designs.	3
	Improved Signage	A clear labelling system for reusable vs. disposable items, and visible signage promoting best practices, could also help foster a culture of sustainability.	3
	Sustainable manufacturing guidance	Maybe a website to automatically suggest the best form of manufacturing in terms of quality, performance, sustainability and speed	5
Resource management	Optimisation tools	For laser cutting, implementing [a] special algorithm that optimises the use of the space of the board	3
	Sustainable materials	Stock more recycled or eco-friendly materials	3
	Improved recycling options	Local recycling of FDM scrapped parts and extraction of heat inserts from scraped parts for reuse	5
	Component inventory	Create a centralised inventory for students to donate or exchange leftover parts	3
Project structure	Greater time allocation	If the makerspace was available for longer periods there would be less waste as people would not be scrambling to finish their projects on time and hoard all of the materials and tools.	1
	More incentives	I can only suggest make it a more prominent point in the mark schemes so people will take it more seriously	2

3.5 Reflections on the student perspective

The student perspectives presented in Tables 1-3 suggest that the students surveyed identify and welcome existing sustainability initiatives in the makerspace. Practices such as the use of scrap materials, sustainable prototyping strategies and the coin budgeting system were particularly well-recognised despite not being explicitly introduced to students as sustainability measures. This suggests that exposure to clear, visible sustainability initiatives as part of experiential learning can successfully reinforce taught sustainability concepts. However, significant barriers remain. Lack of knowledge was a frequently cited issue, alongside time pressures and competing priorities such as aesthetics or durability. These findings align with broader literature highlighting how time constraints and inexperience can hinder sustainable practices in education-based makerspaces. (Honkala et al., 2023).

Students also identified material-related barriers such as the limited availability of sustainable materials and restricted recycling options. Despite repeated mentions of sustainable materials, respondents did not convey a clear idea of what type of materials they believe would fit this criterion. This suggests a possible theory-practice gap in which students wish to engage further with sustainable practices but don't know exactly what this looks like in terms of their material usage. It is important to convey to students that materials are rarely inherently sustainable, and that the way they engage with consumption of these resources typically warrants greater attention. Another example of this is the suggestions around recycling of 3D printed parts and support material. Although a promising avenue, the recycling of 3D prints is currently challenging and resource-intensive, with lingering questions around the mechanical properties and durability of the recycled materials (Hasan et al., 2024). It is important that ESD centres a culture of reduced consumption, rather than leaning too heavily on advances in technology to process waste produced by advances in rapid prototyping (Komatsu et al., 2023; Smith & Light, 2017).

It is also notable that several students independently commented on the energy consumption of makerspace machinery, despite having limited information around these metrics. This demonstrates that students are engaging in sustainable thinking around resource usage even in the absence of direct instruction. This may present a learning opportunity, in which operational data is shared more actively as part of the educational experience, allowing students to properly evaluate energy usage in their making practices.

Although existing guidance and information were identified by students as a positive element of the existing sustainability practices around makerspace-based modules, a clear desire was also expressed for additional educational support around sustainable design and making. Multiple respondents expressed that they struggle to apply academic knowledge in the makerspace, suggesting that despite the inclusion of sustainability education throughout the curriculum and numerous sustainability practices in the makerspace, some gap remains in understanding how to connect these threads. Responses presented in Table 3 demonstrate an appetite for educational interventions such as workshops and online resources to address this gap, indicating that students view the makerspace as an appropriate environment for ESD-based learning.

3.6 Future initiatives

Overall, this case study shows that while the KCL Engineering Makerspace already supports some aspects of sustainability education through curricular integration and sustainability initiatives, there are clear opportunities for growth. Strengthening this connection requires making sustainable practices more visible,

providing clearer guidance, and providing increased learning opportunities that close the gap between sustainable thinking theory and real-world sustainable design and manufacturing practices. To facilitate this, future initiatives will aim to involve students to a greater extent in the management of materials and processes in the space to provide a better insight into what sustainable making means and the challenges involved.

A collaborative effort between academic and technical staff could also explore preparing specialised resources and workshops to help to fill the identified knowledge gaps. Further to this, a greater emphasis could be placed from an academic perspective on the sustainability and life cycle of the prototypes produced during makerspace-based projects, rather than focusing on the theoretical end-product.

4 Conclusions and Recommendations

This work presents the case that curricular-integrated makerspaces hold significant potential for reinforcing ESD within engineering programmes, particularly within the scope of PBL, but that fully realising this potential requires effectively connecting taught and practical course elements. While existing sustainability initiatives were recognised by students participating in the survey, persisting knowledge gaps were among the barriers discussed as hindering sustainable engagement with making. Encouragingly, students demonstrated a clear appetite for more structured educational interventions, including enhanced training, workshops, indicating that the makerspace is seen as an appropriate and effective environment for ESD. A learning opportunity was also identified in allowing students more interaction with behind-the-scenes information such as machine energy usage metrics and recyclability of specialised materials.

For curriculum-integrated makerspaces, there is a need to balance the Maker ethos of open-ended exploration with a responsibility to model and teach sustainable behaviours in a practical setting. If this balance can be struck, there is real potential for academic makerspaces to exist as spaces in which to embed hands-on sustainability in engineering education.

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