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Circular makerspace as means to support sustainable engineering education – instructor, student and facility perspectives

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ABSTRACT

CONTEXT

Sustainability and the related practices in circular design are essential in training future engineers capable of solving the climate crisis. Accordingly, sustainability related learning outcomes have been inserted in engineering curricula, usually in the form of a subject specialising in sustainable engineering but also as single learning outcomes in other engineering subjects. At the same time, we observe an increase in hands-on learning and making in engineering, but the role of that in training sustainable engineering practices has not been explored.

PURPOSE

We explore the role of makerspaces in educating students about sustainable practices. We aim to find out what efforts have been made in using makerspaces as an additional vehicle for training sustainable engineering. We will focus specifically on the viewpoints of the instructors and their observations on what types of practises impact the students as well as the student experiences.

APPROACH

We focus on the University of Melbourne makerspace that has recently made several efforts in turning its practices and facilities more circular. We interview instructors who use the space in their classes and survey students from those classes. The data was analysed to identify best practices as well as barriers to circular design practices in the makerspace in terms of facility management, integration of the space and subject learning outcomes, and observed and experienced impact on student learning.

OUTCOMES

We find that instructors have adapted their subjects to incorporate the circular design practice using the makerspace and find that it benefits the students in making sustainable design a more real experience than only a hypothetical exercise. We find convenience of reusable materials, the end-of-life of projects and the related disassembly, sorting and storage are challenging and costly barriers for fully circular design. The instructors have adopted multiple approaches to tackle this but feel more experience is needed to recommend a best practice and support for student learning.

CONCLUSIONS

We conclude that while integrating circularity in the makerspace as part of multiple engineering subjects has benefits, it is expensive and thus, more studies are needed to understand better how to balance the practice, expense and learning in a circular makerspace.

KEYWORDS

Sustainability, circular design, makerspace

Introduction

Sustainability and the related practices in circular design are essential to help train future engineers capable of solving the climate crisis. In a study of Nordic countries, it was found that sustainability was one of the essential skills for future engineers, but there was not necessarily a big push for it to be included in the engineering curricula (Routhe et al., 2021). Sustainability is explicitly mentioned in many of the Engineers Australia competencies for professional engineers (Engineers Australia, 2019), and accordingly, several subjects on sustainable engineering can be found in universities across Australia.

In this paper, we look at sustainability across different subjects and explore the role of makerspaces in educating students on sustainable practices in engineering. We detail efforts and approaches to use makerspace experiences as an additional vehicle for training sustainable engineering.

Background

Several sustainability programs or smaller initiatives have been developed and reported in the literature. Sustainability related learning outcomes have been inserted in engineering curricula, usually in the form of a subject specialising in sustainable engineering but also as single learning outcomes in other engineering subjects. For example, at the Department of Chemical Engineering at the University of Melbourne, sustainability content was found across the curriculum, but it was embedded at various levels of depth in the subjects (Bury et al., 2022).

At the same time, we observe an increase in hands-on learning and making in engineering, specifically in the form of makerspaces (Wilczynski, 2015). Makerspaces take many forms and vary in size and practices, but most emphasise the role of hands-on activities as part of in-class education (e.g., Wilczynski, 2015, Farritor, 2017). Their role in teaching innovation skills and creating a maker culture has been studied (Forest et al., 2014) but the role of makerspaces in training sustainable engineering practices has not been explored.

Further, Bury et al. (2022) call to action by writing, “It is essential to start thinking about how sustainable development fits into engineering education sooner rather than later to ensure our engineering degrees shape future engineers”. In this paper, we respond to this call by investigating the role of a makerspace, shared across many subjects and departments, in educating sustainability as part of engineering education. Makerspaces act as knowledge centres (Prendeville et al., 2017), and thus they have the potential to share knowledge not only on making but also on circularity across different engineering subjects.

Outside universities, the maker movement has been found to share several goals with sustainability or circular economy (Prendeville et al., 2017). This leads us to believe that circularity can also be incorporated into university-based makerspaces and education. In fact, some initial experiments have been done. For example, Honkala et al. (2023) studied six university makerspaces and found they all had at least basic level knowledge of some circular practices and aimed to improve their spaces towards more sustainable practices. Lee and Manfredi (2021) also found shared efforts in a design school to encourage reuse and recycling. Still, they found students were sometimes reluctant to reuse used items or materials (Lee and Manfredi, 2021).

Given this background, we studied sustainability education within our curriculum and observed the opportunity afforded by the makerspace and its primary support of student projects. Circularity and sustainable choices are present in student projects, and projects are executed primarily in engineering makerspaces on campus. In the next section, we present the results from instructor and facility interviews and reflection, as well as student surveys on how they experienced the sustainability efforts in their subjects and projects that make use of the makerspace. We begin by describing the current circular design practices in the makerspace.

Circularity practices in the makerspace

All the subjects studied use the Telstra Creator Space, a makerspace at the University of Melbourne. The space is a typical university makerspace with facilities to support coursework as well as passion projects. The facility includes sizeable general making and assembly areas with hand tools, laser cutters and 3D printers, special areas for electronics work, a wood shop, and a metal shop. Students and faculty gain access to the space and the equipment by completing specific training for each area or set of equipment.

In the past two years the space has taken active steps to reduce waste and implement circular economy (CE) practices. The specific efforts include placing offcut bins near laser cutters to encourage the use of offcuts before virgin material, which is also made freely available for the space users. Similar practice is also adapted in the metal and woodshops. There is also an initial effort to collect the discarded plastic from 3D prints, but the material is not yet circulated back into use. Examples of these efforts are shown in Figure 1.

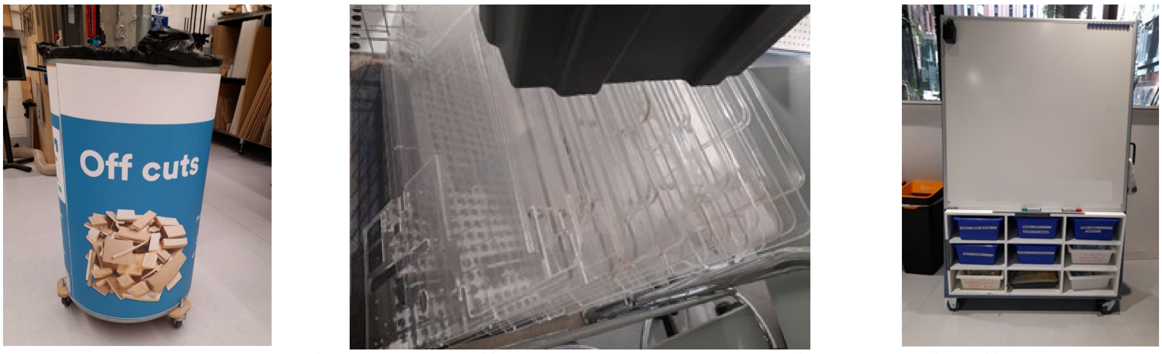

Figure 1: Examples of circularity efforts in the makerspace from the left: off cut bin in the woodshop, leftover acrylic sheets used as sneeze cards previously on campus, and a unit to store used components for certain subjects.

In addition, the space has actively formed networks in the local area and campus to create awareness that they are looking for any and all reusable material others might be discarding. As an example, the space secured a large amount of used acrylic sheets when the sneeze guards from Covid era were discarded (middle in Figure 1).

Another source of used material is a local business, Reverse Art Truck, that upcycles industry waste into reusable material. Items sourced include wooden dowels, discarded fabric, yarn, various small containers, or the inner cardboard tubes from various processes that deal with rolls of thin material.

While significant conscious effort is made in sourcing recycled or recyclable/reusable materials, also virgin material are kept in stock and available for all users. However, cost is a factor that influences material sourcing decisions as well. For example, while plywood would be a more sustainable choice than medium-density fibreboard (MDF), MDF is used.

In addition to materials sourcing and reuse, the space has implemented design review process, where they review student work and discuss alternative means of making, or potential design choices that could result in less waste, use of more sustainable materials or more reuse of materials. Further, the students are encouraged to try virtual or paper prototypes before more extensive prototyping to further reduce material usage.

Outside supporting the current students, the space has also changed their outreach activities towards future students to be themed around circular design.

Approach

Five subjects in mechanical engineering, mechatronics, or industrial engineering were chosen. The subjects were Mechanical Systems Design, Mechatronics Systems Design, Robotics, Sustainable and Life Cycle Engineering and Design and Manufacturing Practice. The subjects were third year undergraduate or master's level classes. One of the subjects (Mechanical Systems Design) is mandatory subject for all students. For the others, they are either mandatory for a specific program or electives.

Faculty responsible for each of the five subjects were asked via email open ended questions related to: general subject description, the use of makerspace, if and how circularity was included in the learning outcomes, content, assignments or assessment, and how the makerspace for used in the circularity efforts, In addition the instructors were asked to detail if they witnessed used of past purchased components, used custom parts, use of off cuts or other similar used materials, and whether they included disassembly of their projects in the class and if so how. The instructors were also asked to reflect on what worked and did not work as well as provide example of both either from their own experience, student assignments or student feedback.

In addition, a representative from the makerspace shared their reflections and observations regarding circularity from the facility point of view.

Finally, a survey was sent to the students of the five subjects involved to explore if and how students were aware of the various sustainability practices implemented. The survey was sent after the semester and after students had received their marks. The survey explicitly asked students if they applied various circularity practices in the subject, how the makerspace helped them with those practices, their own assessment of their project circularity as well as suggestions for different practices. Survey questions are provided in Appendix A. A university ethics approval was obtained for the study.

Instructor Experiences

How circular economy was incorporated in the subjects

The five subjects included had different characteristics in terms of what the main assignment was (project-based class vs other assignments) and if and how circularity was included in the subject. These characteristics are detailed in Figure 2.

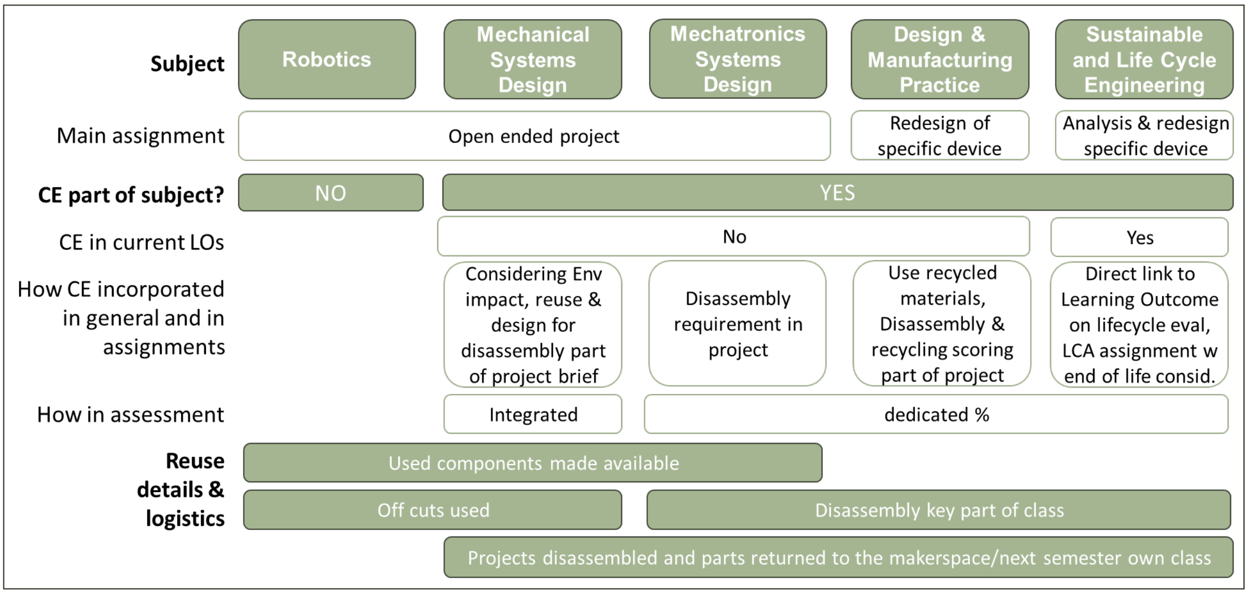

Figure 2: Characteristics of the participating subjects and how Circular Economy (CE) was integrated in them.

The instructors of four of the five subjects had explicit circularity components included in their subjects, but only one of the instructors reported having an official sustainability or circularity related learning outcome. Despite this, all subjects reported some evidence of circularity, mostly reuse or design for disassembly and reuse or lower environmental impact. Robotics was the only subject that had not, at least thus far, included any sustainability or circularity related topics. One subject, Sustainable and Life Cycle Engineering, was dedicated on sustainability and thus the only one where the learning outcomes already included those aspects, but the semester studied was the first time the subject included a hands-on component in the makerspace. The instructors of the other four subjects reported having explicit circularity related goals in the class and it was incorporated into the lectures, assignments and assessment, but in different ways. Similarly, all five had adopted different means to handle the details and logistics to support reuse. These are summarized in Figure 2.

We observe different strategies how circularity was incorporated in the subjects. Three subjects, Mechanical Systems Design, Design and Manufacturing Practice and Sustainable and Life Cycle Engineering all included some form of environmental impact assessment, but they were all different. In Mechanical Systems Design, simple environmental impact indicators were given to the students, based on Life Cycle Assessment (LCA) of the components and materials made available to the students, and the students were asked to include the indicators in their design decisions as well as in the final Bill of Materials. In Sustainable and Life Cycle Engineering the students performed the LCA themselves as part of the class and assignments, and then it was used to propose a new design. In Design and Manufacturing Practice the students were instructed to use disassembly and recycling scoring systems to assess and improve the design of a given device. In Mechatronics Systems Design, disassembly after the projects was a mandatory part of the project, but no scoring or assessment was used. In addition, Design and Manufacturing Practice used post-consumer use plastics as material in making new parts and it was compared to parts made from virgin material. In addition, all four subjects required discussion or inclusion of reuse, circularity, etc. as part of the reports.

The four subjects that had circular economy related aspects in their classes, had chosen two different ways to incorporate it in assessment. For Sustainable and Life Cycle Engineering, where CE was part of the leaning outcomes, there were two dedicated assignments worth 10 and 20%. Mechatronics Systems Design dedicated 10% to the disassembly assignment and Design and Manufacturing Practice had questions in two assignments dedicated to disassembly and recyclability and they were worth 15% of the total mark. In contrast, in Mechanical Systems Design, the assessment was integrated into the project assignment with no dedicated percentage, but the top mark was only possible if environmental impact was taken well into the account in design decisions and the environmental impact was lowered.

In terms of the practicalities related to reuse, the five classes had adopted two to three different strategies (Figure 2). Three of the classes made used components (motors and basic electronic components) available in the makerspace. While all students from all subjects had access to the offcuts in the makerspace, only two subjects saw them being used, with only one explicitly encouraging off cut use. This was partly due to the nature of the subjects, the two subjects working with specific devices had no use for off cut materials. In Mechanical Systems Design class, the students were also given parts made by past students in the same class, such as gears, cams and various structural parts, but the instructor mentioned that they were not really used in the projects. However, it was noted that students were observed to use those as inspiration. For example, the instructor mentioned how one team chose to use a D-shaft after seeing D-shaped hole in the used gears and another student team mentioned being inspired by seeing a linkage shape that has a partial gear at one end to try a similar approach in their project.

Interestingly, also the one subject that did not explicitly include circularity in the subject, Robotics, also reported evidence of component reuse and offcut use. This is likely due to the use of the makerspace, which has several used items available. For example, used acrylic sheets were observed being used in the robots. However, some of the electronic component reuse may also be due to students being familiar with them. The instructor reported that they saw several components from a pre-requisite class (Mechatronic Systems Design) in the robots.

Best practices and challenges

Since all subjects used different and mixed approaches and three of the subjects were doing it for the first time in the semester studies here, we are not able to quantify conclusions on which aspects were most successful or suited best for specific cases, but we rather summarize what the instructors felt worked, if there were any iterations, how the evolution has improved circularity or learning of it. We also share challenges the instructors reported.

All five subjects report successes. The instructor in Sustainable and Life Cycle Engineering reported that the students were engaged and enjoyed the new hands-on parts (disassembly of a device in the makerspace with end-of-life analysis and sorting for reuse). The practical assignment also supported the students' other assignments by allowing the students to appreciate the complexity involved in design decisions and environmental impact. In the semester studied the instructor had purchased new devices to be analysed and disassembled but hopes to move to analysing used devices instead to be more in line with the circular principles in the how the assignments are set up as well. The set of devices disassemble this time contained several parts that are hard to reuse and thus most of the newly purchased devices ended up in landfill.

In Mechatronics System Design the disassembly went well, and it was useful step in enabling the use of past components the following semester. Given the open-endedness of the project, the instructor is looking into how to incentivise the students to use these used components more. One of the potential ideas is to include a design review to support the use of used components. In Mechanical Systems Design, the projects had been disassembled and components reused for a couple of semesters already. In contrast to Mechatronics Systems Design, the disassembly was handled by the tutors after the semester ended. This was done to give students more time to complete their projects and to ensure the components were well organized with a full inventory before the next semester. This worked but the instructor is concerned of the cost of using tutor time for it. In addition, the students' claims for ease of disassembly are often overly simple (e.g., we use only non-permanent joints such as bolts), where in practise they had used multiple different sizes of fasteners, often is hard to access places and occasionally hidden glued parts, all of which resulted in long disassembly times. Including the disassembly in the assignment, as it was done in Mechatronics Systems Design, could help students learn it better but would come at a cost of leaving less time for the project itself.

Further, in Mechanical Systems Design, the projects are open ended, but narrow such that the students can design the project with the components provided (motors and electronics components). This results in almost perfect reuse. Only a handful of outside components can be seen in the final projects. There is an attempt to have student reuse also the custom-made parts such as gears, cams and other mechanism made by the past students, but only a handful of projects seem to take advantage of this. It is not known why, but the instructor assumes it could be due to convenience, a new gear pair is easier to draw to specific requirements and laser cut than to find a suitable pair from a bin of unlabelled used parts. Motors, sensors etc. on the other hand, are clearly identifiable and have a known function, and thus their reuse seems easier for the students. Both the instructor and students, according to the instructor, found it important that all components were available in the makerspace.

In the Design and Manufacturing Practice subject, the instructor reported that the disassembly analysis is good at highlighting the difficult-to-disassemble joints and that the use of recycled material in making new parts was successful. However, the students do not have enough experience working with recycled polymers, fabrication, and assembly to be able to judge if something will function or not and so feasibility assessment was difficult. Further, the equipment used to make recycled filament from plastic waste was laboratory equipment which resulted in filament with larger diameter variability than commercial grade filament. This resulted in prints with void defects and the occasional plugged nozzle. These outcomes were observed late in the subject, and so in future years the tasks will be inverted, and the students first provided with an assembled machine which they can operate to get experience, and then disassemble to directly understand disassembly difficulty. Then redesigning the parts for simpler fabrication and assembly is more tangible, as well as for improved printing. Further, the makerspace does not currently provide means to use recycled plastics for 3D printing (equipment warrantee issues) and it is hoped this will be the case in the future.

For Robotics that did not include any CE elements, the project itself was deemed challenging enough without the added CE element, but the instructor mentions how there could be ideas to balance the difficulty of the project as is and the added CE element.

Facility Experiences

The different circularity initiatives that the space has taken were summarized above. Here we reflect how these practices work, have evolved and how it is visible in the student and instructor behaviour.

Overall, significant use of offcuts and recycled materials was observed thus indicating that the initial efforts seem to work. However, multiple challenges were observed.

One challenge was that all new items often come well labelled and are thus easier to find, identify and thus use. For example, new fasteners are sorted in their bins by size. Used fasteners, on the other hand, tend to be mixed and there have been debates if sorting them is worth the time and if they should be sorted back with the new fasteners or separately. As a solution, there has been discussions to create a visual well-organized storage area for used items. It is expected to make the locating of useful used items easier, but the effort to keep it sorted and well labelled is expected to remain a challenge. There is also a preference for new parts especially for electronic components, where it may be initially unclear (e.g. not visible immediately) if all the parts are fully functioning. Students may find malfunctions in one of the several analog output ports of a microcontroller, which could cost them many hours of troubleshooting. This reduces the trust in, and the willingness to opt for, the recycled parts. Teaching students systematic troubleshooting approaches, such as testing ports prior to using them, could help alleviate this issue.

Another observation was related to the design reviews. CAD files are reviewed as a standard part of 3D printing before allowing the print. As part of this review, it is sometimes suggested that the student should make their part by other means, such as laser cutting. This naturally results in a redesign of the part and students are generally not pleased to hear this recommendation even if they are told it will be a more sustainable choice. Convenience being the deciding factors was observed also elsewhere. It seems that most wanted to do the right thing, but if it required acquiring other materials and the less sustainable was easier to do, the easier option was chosen. As a future development, efforts should be made to make the more sustainable choices the easier choices.

Finally, circularity can only work if the materials and components in the space also make their way back to the space. While some subjects actively did this, it was observed that students need to be incentivized to contribute back to the reusable materials. Along the same lines, it was observed that some instructors seem to have emotional attachment to the student effort and work and were thus hesitant in dismantling student work.

One bonus benefit of having miscellaneous used materials visibly available for the students was that it seems to support student creativity. The students were observed standing by the supplies and either coming up with or changing how they might make the device they were building. Given creativity was not the main topic of this study, it was not pursued further.

Student Experiences

To understand how the practices implemented by the faculty and the facilities were seen or used by the students, students were surveyed about their experiences. Sixteen students responded to the survey: 1-6 students per subject but non from the mechatronics subject. Given the overall low sample size, results are presented as students suggestions and not analysed as representative of the class experience.

All respondents applied at least one of the circular practices in their project, either by reusing material wastes or off-cuts, previously used parts or components, building for disassembly or by disassembling their own project for re-use. Clear differences can be noticed between subjects, with all students from Design and Manufacturing Practice mentioning the design for disassembly feature of the project for example. These differences tend to reflect the practices explicitly included in each subject: students applying at least these elements, sometimes complemented by other practices.

Regarding how makerspaces assisted the students in these practices, most respondents mentioned the availability and visibility of the various recycling bins in the makerspaces as an obvious circular practice incentive. A respondent even mentioned that visualising the quantity of material in the waste bins was an important learning point. Five students effectively reused MDF or acyclic off-cuts in their projects, two reused existing 3D printed parts and two reused other components. Overall, the student response was positive on learning to work with recycled and repurposed parts and materials, and having exercises in ensuring their projects are design and built for circularity. However, given the low response rate, further studies are needed to understand how the different efforts in the makerspace and the different means of implementing CE in the classes are experienced by the students.

Conclusions

Makerspace is a key part of all subjects studied and it supported the circularity efforts in the subjects in different ways by providing space, materials, storage of reusable material and components and by supporting students in design reviews. We found that the efforts the instructors and facilities made supported one another and the students were aware of these practices as indicated in the survey responses.

From the faculty perspective, we found different levels of implementation of circularity practices. In component and part reuse, the students can be given specific dedicated parts/device, access to set of components that can be used, allowed to use anything they wish but encourage to reuse. Similarly for the materials used or devices analysed students can be provided new or used materials or devices. How well students learn or incorporate circularity can be assessed separately, as part of other design decisions, or not at all. Similarly, circularity can be part of a class whether it is included in the subject or assignment learning outcomes or not. We observe a spectrum of efforts that we hope provide inspiration and example for others to experiment with.

Interestingly, in the one subject that did not include any circularity aspects, the students were still observed reusing components rather than ordering new. This could be an indicator that the makerspace indeed works as a knowledge centre (Prendeville et al., 2017).

The open challenges and areas for future work include the management of time, effort and cost it takes to disassemble, sort and store reusable materials as well as how to best incentivise their use. It also remains open how well the learning from one class supports the following classes. It is hoped the makerspace as a common space across the classes, supports these continued circularity practices across subjects, but it remains to be seen. Further, not all subjects are willing to adapt circularity practices. Here we included one in the study, but the facilities reported others. The hesitation, as observed here, is from the faculty point of view. It would be interesting to study how much the common practices in the space influence those subjects. Would circularity be seen also there, like it was seen (to a minor degree) in the Robotics class studied here.

Finally, communication between the instructors and the team in the makerspace is important. The two sides are not always aware of the practices, demands or goals of the other side. For example, the facility side reported several cases of guiding students to more sustainable fabrication, but no instructor was aware of it. Similarly, not all instructors were aware of the design reviews in the makerspace.

Overall, makerspace practices such as making recycled parts and materials available supports the circularity efforts and helps promote them further. More research is needed to understand and formulate the most effective means to support student learning of sustainable approaches and processes.

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Appendix A – Students survey questions

1) What circular practices did you observe in your subjects using the makerspace (TCS)?
2) How did the makerspace helped you with circular practices?
3) In your projects, did you use any previously-used purchased components? If yes, what components?
4) What components did you re-use?
5) In your projects, did you use any previously-used custom fabricated components or parts (e.g. laser-cut parts or 3D printed part produced by others)?
6) What part or components did you re-use?
7) In your projects, did you use any previously-used off-cut materials?
8) If yes, what material did you re-use?
9) In your projects, did you design for the project to be disassembled?
10) What steps or design choices did you make to ease or help the disassembly?
11) In your projects, did you disassemble to provide components or materials for re-use? What type of parts did you disassemble?
12) How did you assess your project on circularity?
13) What would you like to do differently?