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Towards Circular Design and Manufacturing – Lessons Learned from University-Based Makerspaces

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Abstract

Makerspaces are increasingly common in universities and do their part in training students for design and manufacturing in industry. This provides an opportunity for universities to use the makerspaces as testbeds for future design and manufacturing. In this paper we focus on the environmental impact of university makerspaces. Previous literature has examined what is the environmental value and impact of makerspaces, and how these topics are being discussed in the maker community. This qualitative study focuses on understanding the daily practices and methods related to circular material flows. We investigate the status of material circularity in university-based makerspaces and mechanisms that can accelerate the shift towards more environmentally sustainable practices. Thirteen interviews in six different makerspaces in Finland were conducted. We find that many circular themes can be linked to the makerspace and their culture of making. A wide range of different solutions related to recycling, reuse, and, for example, sustainable material use are applied. The identified actions used for fostering circularity can be grouped into five groups: Design, Production, Use of a prototype, End-of-Life, and External factors. However, while a wide variety of actions have been taken to increase the material circularity, many challenges remain ranging from the lack of cooperation to materials-related knowledge gap. These results can be used to turn university makerspaces more circular, which in turn can be used to both train students for more future-proof sustainable design and manufacturing as well as further develop improved circular design practices.

Keywords: Circularity: Makerspace; Circular Design, Circular Manufacturing

1. Introduction and background

Makerspaces are increasingly common on university campuses and elsewhere enabling users to design, fix, and fabricate physical artifacts [1]. They provide tools, equipment, and meeting spaces that enable rapid prototyping etc. They aim to demonstrate the value of hands-on prototyping, design-driven education to stimulate student creativity and entrepreneurship [2]. University-based makerspaces take several forms from teaching labs to large multi-disciplinary makerspaces. Most offer both a physical space and a community around making [3]. The increase in making has resulted in discussion about the makerspaces' environmental impacts and how they support circular economy. Makerspaces can foster circular economy by creating networks, where valuable resources including knowledge and scrap materials, can be shared [4]. However, research shows that students may be reluctant to share and may not be aware of options to reuse and recycle [5]. There seems to be a lack of research in the field [4,6]. To date, little research has focused on the daily practices and challenges linked to them. University maker spaces mimic design firms or departments in industry and train the future product designers. This provides an opportunity to study current challenges in an industry like setting.

The increasing stress on global resources and climate change as well as the tightening of environmental legislation

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and increasing interest in sustainable consumption have promoted a shift towards circularity in different disciplines [7-8] and new means to capture value via circularity [9-10].

Makerspaces can act as knowledge centers and spaces for circular design solution development [4]. In fact, most maker-spaces have at least a basic awareness and some capacity for environmentally friendly practices [4, 11]. There are two crucial factors that impact environmental awareness within the maker community and sustainable culture formation: a shared vision that is adapted early, and sustainability champions within the makerspace [8,11]. On the contrary, the lack of expertise, resources, and guidelines hinder the shift towards more sustainable makerspaces [6,8]. Several examples of circular practices in makerspaces can be found. These are grouped based on similarity in (Table 1).

Table 1. Examples of makerspace circular practices found in literature.

	Circular practices
Material Selection	Bamboo and Polylactide (PLA) mix for 3D printing [8]
	Prototyping out of waste [8]
	Bio- and putrescible plastics, mushroom, natural dying processes [8]
	Use of local waste stream as a material resource [4]
Production	Vertical farming [8]
	Use of mushroom to grow materials [8]
	Efficient production methods [8]
Product life extension	3D printing to produce spare parts [8]
	Community repair meetings [4]
	Collection of products and materials from the local community for upcycling meetings [4]
Material flow	Sourcing materials from waste meetings [4]
	Off-cuts collected and stored visibly meetings
	Waste 3D filament used as reparative glue [12]
Guidance and guidelines	Labeling valuable scrap materials meetings [4]
	Knowledge sharing of good design practices meetings [4]
	Instructions for efficient machine use meetings [4]
	Best practices reuse, recycling & material choice manual [6]
	Sustainable prototyping lifecycle model [13]
Skills	Recycling and repair workshops meetings [4]
	Co-creation activities for sustainable design [14]
	Partnership with e.g., experts to raise awareness meetings [4]

This study builds on this by studying the current practices, challenges, and opportunities to increase *material* circularity in university-based makerspaces. The research questions are:

Q1: What are current practices to increase material circularity in university-based makerspaces?

Q2: What are the current challenges and opportunities in university-based makerspaces related to material circularity?

2. Approach

2.1. Data collection

In this multisite qualitative case study six university-based makerspaces in Finland were selected based on convenience, while still ensuring good representation of a variety of different business models, activities, and values. Two prototyping- and productdevelopment spaces, one digital design and additive manufacturing research space, one metal workshop, and two from the FabLab network (fabfoundation.org) were selected. The number of staff for the spaces was between 2-59, 5 being the most common. Thirteen technical and academic staff members, all prototyping professionals with an understanding of makerspaces' daily activities, such as material use, recycling and guidelines, or management level details took part in ten semi-structured interviews in November 2020. Two interviews had more than one participant. The interviews were conducted face-to-face or via video, depending on the interviewee's preference and location. The interviews lasted 50-90 minutes (mean 57 min). Interviews were conducted by the first author in Finnish or English depending on the interviewee. All interviews were recorded, transcribed, and translated into English. The interview covered five broad topics: introduction, prototype design and materials, prototype production, end-of-life, and concrete examples. The topics were selected based on Table 1 and prototyping literature. Details can be found in [15].

2.2. Data analysis

The transcripts were thematically analyzed in Atlas.ti. Thematic analysis was selected as it allows to identify, evaluate and categorize comprehensive and complex data sets in detail to find patterns. First, 361 quotes were classified under 43 initial codes. These were then iterated and further divided into different themes. After multiple iterations, codes were grouped under six themes: Material selection and machines; Reduce, reuse and recycle principles; Space; Information sharing; Cooperation and partnerships; and lastly, Culture. Each theme was also further divided into subcategories (Table 2).

3. Results

We found 33 factors in 5 categories that impact material circularity in makerspaces. These are summarized in Table 3.

3.1. Material Selection and machines

As many interview questions were linked to material selection and machines, this was the most commonly occurring theme. Prototyping spaces are often "general stores" with extensive material selection. The material streams were both scattered and versatile. Plastics, plywood, and PLA or ABS for 3D printing were the most prominent material groups, as they are easy, quick, and relatively cheap to use. Other popular material groups were metals, wood, and basic materials such as card- and foamboards. Students often use cardboard or wood as they are perceived as safe and familiar materials. Materials such as particle board or plastics (MDF, epoxy, and acrylics) were seen as challenging and undesirable materials for prototyping purposes due to safety reasons and hazardous compounds. Many interviewees described that they would prefer safer alternatives to these materials.

In addition to using these traditional prototyping materials, two makerspaces had conducted bio- or upcycled material-related experiments. One interviewee described that they have tried straw for packaging and mycelium to grow composite material. However, only one space, described as a research institute, has tried biomaterials in 3D printing and model making on a larger scale. They have tried sawdust, reindeer bone dust, wood waste products, sugar, and fly ash from coal power plants as raw materials for 3D printing.

Table 2. Main themes identified and a sample quote for each main theme.

Theme	# quotes	Sample quotes
Material Selection and machines	**129**	"If you take recycled material off the shelf, then it can be hard to know what it is."
Material innovation	2	
Materials	35	
Materials (bio or recycled)	24	
Materials (common)	18	
Tools & Machines	38	
Material value	12	
Reduce, Reuse & Recycle -principles	**121**	"Laser cutting, when holes are made, creates round discs. I keep them in a box and use them as spacers or stencils, for example. They are also good for Lego -type of prototyping."
Behavior	5	
Design	5	
Economies of scale	7	
Lack of resources	7	
Recycling	27	
Reducing	8	
Reuse	29	
Waste	33	
Space	**30**	"Materials must be able to store in order to keep them circulating."
Cleanliness	8	
Inventory	3	
Space and storage	19	
Information sharing and instructions	**38**	"There is an orientation exam before entering the space."
Information sharing and instructions	21	
Rules and practices	11	
Teaching	6	
Cooperation and partnerships	**48**	"Cooperation within the campus works in a way that we just spread the word among the right people."
Cooperation	31	
Partnerships	9	
Community	3	
Platform	5	
Culture	**9**	"We are constantly looking for better and more efficient solutions"
Culture and change	7	
Strategy	2	

Many interviewees were interested in using biomaterials or upcycled materials and saw their potential but have not tried them as captured by an interviewee: "*There is potential. Much more should be utilized. Especially further processing and reusing [of materials]. Let it be sawdust or something else, it is better to use that for something else first than burn."*

While clear opportunities were seen in new materials and upcycling waste streams, many interviewees emphasized the importance of material features and design and how they fit prototyping purposes. This can be challenging with bio- or recycled materials. For instance, one interviewee mentioned that replacing Styrofoam with paper pulp-based biomaterial can be challenging due to the needed material properties such as its ability to withstand moisture.

In addition to the material properties, three interviewees mentioned economies of scale regarding the use of bio- or upcycled materials. All three wondered whether the volumes would be big enough if they were to consider using makerspace's own waste streams for new materials.

When it comes to tools and machines that makerspaces are using, the most used machines are 3D printers and CNC machines. Many emphasized that they are afraid that the number of people who understand manufacturability is declining. The same applies to material-related knowledge and appreciation. When asked about the challenges related to material circularity in makerspaces, an interviewee described that material knowledge and poor material identification create obstacles to reusing and recycling. Especially after materials have been used or processed, it can be challenging to identify the material. The interviewee wondered if a marking system for recycled materials could enhance the material identification or teach at least the most common ten prototyping materials for makers before they start.

In terms of appreciation of resources and materials, one makerspace had tried to add price labels to the more valuable materials. This has had an impact on users' behavior, even though the material is free for the students to use. They have been using this as one solution for waste reduction.

3.2. Reduce, reuse and recycle -principles

Reduction-, reuse- and recycling-related principles were the second most quoted theme in the interviews. When asked about reducing production-related waste, the most common answer was a proper prototype design. Many interviewees mentioned that they try to teach new users and share information related to design. One interviewee mentioned that compromises can be

Table 3. Identified factors and actions that impact material circularity

Design	**Production**	**Prototype use**	**End-of-life**	**External factors**
Selection of low impact materials	Optimization of production techniques	Optimization of initial lifetime	Reuse and disposal of materials	Factors contributing to circularity
Biomaterials	Prototype design	Remanufacturing	Biodegradability	**Space -** Facilities & cleanliness
Recyclable	Minimal production waste	Upgradability	Composability	**Culture -** Strategy and awareness within the community
Recycled	Simplified production	Modifiability	Recyclability	**Cooperation -** Local& Global collab. For material and knowledge transfer
Biodegradable	Industrial symbiosis	Dis- and reassembly	Reuse	**Information sharing and skills –** Signs, courses, guidelines, …
Renewable	Reduction of material use	Durability	Upcyclability	**Other Resources -**Time and staff members
Upcycled	Minimal energy waste		Used component inventory	
Waste stream	Use of scrap for testing		Sharing	
Material innovations	Prototyping with used materials			

made in material quality, especially during the first phases of prototyping. They mentioned that it can be acceptable to have holes in a prototype even if not in the final product if it does not impact the functionality. Another interviewee described that they recommend testing the machine settings with scrap material, which decreases the number of failures and the amount of production waste generated.

Production waste and surplus materials are typically reused and recycled in the space as far as possible and seen worthwhile. However, there are notable differences between the makerspaces. Some spaces try to upcycle most of the excess materials, whereas others emphasized the importance of cleanliness and space over reuse. Excess materials are usually stored in the space, waiting for other applications. However, lack of space can hinder material reuse. The interviewees described different purposes and applications for surplus materials, ranging from using scrap materials to machine set-up testing to reusing surplus plywood as mixing sticks. One interviewee explained reusing round discs leftover from laser cutting as spacers or for Lego-type prototyping and ABS plastics as ABS glue.

Similar principles apply to used prototypes. If prototypes are not taken away by the makers, they are typically disassembled, and valuable components are stored for further use. Some prototypes are kept as inspiration sources for others. However, few stated that it is not allowed to leave prototypes in their space, and thus makers themselves are responsible for reusing or recycling their prototypes.

To promote the use of these used materials, both from production and used prototypes, most have developed their own systems, such as Wall of Boxes, Supply Cave, (Fig 1), or Recycling Trolley, around reuse of, for example, scrap materials and components. The basic idea behind these systems is to ease the finding and use of available resources. The Supply Cave was described as "*a wonderland of materials. It is quite unique. A room where there a lot of different materials are kept, and students are free to use them. Basically, anything that you want is there. Also, a lot of random things like car parts and blenders. […] Most often people just go there and see what is in there.*" However, each system has its own specialties, such as functionality, movability, or system's appearance.

Fig. 1. (a) Shelves in the Supply Cave; (b) Wall of Boxes

Reuse and recycling can also save costs for both makers and the spaces. Many spaces offer used or recycled materials for free, which promotes their use. Money can be an incentive for recycling for many makers and startups. One interviewee described that recycled materials may be even better for prototyping purposes as it gives the freedom to test and fail without fear of ruining a valuable material.

When asked about the solutions that are already improving the material circularity or could enhance that in the future, many methods were mentioned varying from selling or offering used resources through different kinds of platforms to reusing of PLA and plastics. For example, one interviewee stated that they used yard sales and another space sold unnecessary resources online. Two interviewees described methods based on either melting and molding of recycled materials or creating new biomaterial filaments to reuse plastics or recycled PLA.

In addition, five interviewees stated that a university-wide solution for material recycling or reuse could improve their circularity rates. They were hoping to have a solution for material sharing and loaning, such as a website or a shared space for both new and recycled materials. One interviewee proposed that the university could have a space for material upc- and recycling. This space could offer specific resources and methods, such as injection molding machines and grinders, for material processing that are neither viable nor profitable for single makerspaces.

When discussing opportunities or solutions, some interviewees mentioned behavioral methods focused either on making the unwanted behavior demanding or simplifying the desirable actions. For example, having new materials further away promotes the use of recycled materials. Recycling in the makerspace should be done as obvious as possible so that users would not have to make the extra effort for it.

Two bigger challenges emerged during the interviews: economies of scale and lack of resources. Many interviewees questioned that as the waste streams are so scattered and relatively small, is the ratio from used resources compared to benefit received high enough. Two interviewees also said that they already have the needed equipment for plastic filament recycling, but due to the lack of time or employees, they are not able to do it. Many interviewees also described that failed 3D prints are challenging to recycle.

Wood or plywood were the most common waste material. Models made from wood are usually large, which impacts the amount of waste generated. In addition, nails, paint, or screws are also often utilized with wood-based models, making them more challenging to recycle. However, most interviewees still stated that single waste streams are small as we are talking about prototyping spaces. One interviewee challenged the idea of waste saying that if the prototype has fulfilled its function and answered the intended questions, material used for it has not been wasted. Another interviewee similarly highlighted how prototypes are part of the product development process. Thus, in the bigger picture, used resources during prototyping can save resources in the later phases.

3.3. Space

Space was one of the most highlighted matters since it is directly proportional to the number of used materials and components they can store. However, one interviewee highlighted that even when they have enough space for storing different materials, the problem is that students do not know much about the available resources and thus are dependent on staff guidance. Sometimes even staff members are not able to remember all the available stock. It is easy to take materials in, but hard to remember what is already available. Therefore, many interviewees were hoping to have an inventory system as a solution for this described issue.

Cleanliness was also mentioned as a challenge by almost every interviewee. One said, "*Cleanliness contributes to making it easier to find what you already have and to store materials*." Usable materials may be thrown away without proper storage facilities since they can potentially cause safety risks for the users.

As a solution, many interviewees mentioned a university wide and central warehouse could help them store and reuse materials. A few interviewees described that they have a common material center, but it is only used for new material. Three interviewees would like to expand that operation and use that storage also for used and recycled materials. Staff from different makerspaces could then use the storage to either find new and recycled material or recycle resources that they do not need. Some interviewees also suggested that better guidelines for material storage could improve their material flows. Guidelines and better signs in a makerspace's material storage could facilitate the user experience and clarify which materials are being stored and further reused.

3.4. Information sharing and instructions

Although information sharing methods were not directly included in the interview scheme, many interviewees found it one of the most critical yet challenging areas that influence their daily activities. Many information sharing methods are used in makerspaces, such as guidelines, labeling, instruction booklets, and courses. Many interviewees described that reuse- and recycling points are clearly marked with icons and/or text and placed next to the machines, to make it easier for the user to both find and use the material collecting points. One interviewee also mentioned an instruction booklet, that may be distributed to new makers to introduce space safety and give an overview of available prototyping materials. Another space has started using an introductory course as a platform for introducing the life cycle concept for students to question what happens to the prototypes when the project course ends.

In addition to the opportunities related to information sharing unsolved challenges still occur. Many valuable and important things still depend on whether the staff members can give the instructions to new makers or not. Three interviewees, who are all working close to daily activities as either workshop managers or masters, described situations where they must follow and guide the users through the process to ensure safety or, for example, reduce the amount of production waste.

A similar challenge can be linked to how these spaces reduce production waste. The most common way is to guide the user to test the settings with scrap material. However, in many cases, these instructions were shared solely by word of mouth. This also leads to the question of how to guide users outside the regular working hours when the staff is not available, as highlighted in one interview: "*This is a space where people are clearly working in the nighttime. Challenges increase because you need to make sure that space serves the users. Everything should be obvious and visible.*" As a solution, some spaces use overlapping methods for information sharing, such as courses, signs around spaces, staff members, and exams that need to be passed before entering the space.

3.5. Cooperation and partnerships

Most of the interviewees collaborate with local actors, startups, or global makerspace networks to varying extents. The most mentioned collaboration benefits were knowledge sharing or fostering the ideation process, and it was described in both local- and global cooperation. Similar examples were given for global collaboration, and for example, one interviewee emphasized the importance of their global and active network, which enables the international knowledge flow. Another interviewee described that they have an international partner who has been helping them develop the space from the beginning. To enhance the collaboration between their spaces located on different continents, they have built a telepresence robot (Fig 2), which can be used as a communication tool between two workshops.

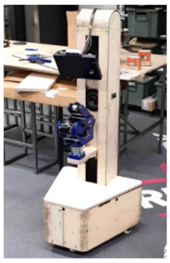

Fig. 2. Telepresence robot at the J. Hyneman Center LUT (photo by M. Kasurinen).

However, while the international networks and knowledge sharing seemed to benefit many makerspaces, four interviewees highlighted challenges related to within the campus cooperation including one saying "*There are no organized meetings; it would be nice to have monthly meetings with campus labs. We are connected to other FabLabs, but we are not connected to the closest ones.*" Many interviewees hoped to have more transparency related to materials and resources that different campus spaces have through more active cooperation. The second most mentioned benefit was related to reuse and sharing different materials. Collaboration both within the campus and with local actors has offered ways to either find new owners for surplus materials or discover usable "waste" materials for prototyping purposes. In most cases, this material cooperation within the campus is based on word of mouth and knowing the right people to contact. Additionally, two prototyping spaces have tried collaboration with other local actors to increase material circularity. One makerspace has collaborated with a local scrap shop, and the other has tried cooperating with a nearby landfill to find usable waste streams, which could be further reused as prototyping raw materials.

3.6. Culture

Culture was brought up by only one makerspace. However, those interviewees emphasized the importance of culture when asked why sustainability related matters are heavily considered in their operations. They said that when building a new makerspace, the culture among the university and the people involved can have a notable impact on the future direction and their tendency towards circular solutions. The interviewees mentioned that it was decided in the beginning that both sustainability and material circularity-related issues will be considered in their operations, and sustainability is also strongly linked to their university's strategy. In addition to the university's culture and the people involved in the maker-space's activities, one interviewee mentioned their culture of change and continuous improvement as essential parts of their operations. They said: *"Our place will never be finished. We are constantly looking for better and more efficient solutions through a change; we do not want to stay put. Our place really is "recycled". It is a prototype of a prototyping space that is being tested all the time to see if it works and what works. Thoughts are also recyclable; we tell them everywhere and borrow them everywhere."*

4. Discussion

We studied current ways to increase material circularity in university makerspaces by exploring the current challenges and opportunities. We found a wide range of solutions related to recycling, reuse and sustainable material use. Diverse recycling solutions, and carefully considered materials use and model design, were seen as the easiest steps toward circularity. For example, many spaces have developed different systems, such as Supply Cave, or Recycling Trolley for reusing scrap materials and used components. Material streams are generally well reused. The study revealed that interviewees have developed many ways to reuse surplus materials, such as turning PLA filaments into glue or using laser cutter scrap as spacers. Also, different methods for information sharing, cooperation, and storing were identified.

Although the general level with prototyping materials, machines, and recycling is similar among the participated makerspaces, apparent differences between spaces were detected. While a certain level of circular actions is adapted in most spaces, some have taken a step further. This could be due to most of the methods being individual or bottom-up approaches, which is related to some of the remaining challenges such as information flow and the lack of cooperation, space, or other resources, such as time.

Cooperation with local partners and stakeholders was a highly debated theme by providing solutions for both knowledge- and material sharing. Similarly, the lack of local cooperation was seen as a significant issue. Especially the collaboration within a campus was seen either as a challenge or enabler for circular practices. Previous studies have not addressed the mentioned challenges as such but, for example building local relationships, makerspaces can create industrial ecology networks [4], but this is many times failed to achieve due to lack of time or knowledge. Perhaps scaling up or spreading these bottom-up approaches can help, but it is not clear how to best achieve it, but a more strategic vision and sustainability champions may help [8]. If circularity was integrated in strategy, it could potentially help with the resource challenge as well.

Overall, the findings we mostly in line with past general makerspace literature, with the exception of product life extension not playing a large role in these prototyping makerspaces and there was additional emphasis on the external factors such as need for collaboration and knowledge sharing.

4.1. Limitations & Future directions

A limitation to the study is that the sample is relatively low and only from one country. This may cause a potential bias to the interview data set, as some of the problems or solutions may be linked to, for example, organizational or national culture.

Future research could study the impact of the current actions, investigate actions not taken and the potential impact of those as well as expand beyond material circularity. Further research is also needed into how to scale up bottom-up activities, how to improve information flow and collaboration – the key challenges identified beyond lack of resources.

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