

ABSTRACT

Title of Thesis: **UNDERSTANDING SUSTAINABILITY
PRACTICES AND CHALLENGES IN MAKING
AND PROTOTYPING**

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Democratization of prototyping technologies like 3D printers and laser cutters has led to more rapid prototyping practices for the reasons of research, product development and individual interests. While prototyping is becoming a much easier and faster process, there are many sustainability implications neglected. To investigate the current sustainability landscape within the realm of making, we conducted a comprehensive semi-structured interview study involving 15 participants, encompassing researchers, makerspace managers, entrepreneurs, and casual makers. In this paper, we present the findings from this study, shedding light on the challenges, knowledge gaps, motivations, and opportunities that influence sustainable making practices. We discuss potential future paradigms of HCI research to help resolve sustainability challenges in the maker community.

UNDERSTANDING SUSTAINABILITY PRACTICES AND
CHALLENGES IN MAKING AND PROTOTYPING

by

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Table of Contents

Acknowledgements	ii
1 Introduction	1
2 Related Work	4
2.1 Sustainable Fabrication Technologies	4
2.2 Approaches for Promoting Sustainable Practices	5
3 Methods	7
3.1 Recruitment	7
3.2 Research Studies	8
3.3 Data Analysis	9
3.4 Positionality Statement	10
4 Findings	11
4.1 Types of Waste: Those Wasteful and Those Still Usable	11
4.1.1 Material waste produced via various machining	11
4.1.2 Brand-new components, intermediate prototypes, and archived projects	13
4.2 Handling Waste: Trashing, Keeping, and Reusing	15
4.2.1 “They are all going to the trash bin.”	15
4.2.2 “I wish I could keep them all.”	17
4.2.3 “The motor got three more lives.”	18
4.3 Challenges in being sustainable	21
4.3.1 Lack of procedures and equipment	21
4.3.2 Sustainable actions may not be worth it	23
4.3.3 Knowledge gap	24
4.4 Achieving Sustainable Making Through Implicit Means	25
4.4.1 Reducing design iteration	25
4.4.2 Better organization	27

5	Discussions	30
5.1	Putting Sustainability at the Forefront of Design Processes	30
5.2	Developing Technologies to Streamline Sustainable Practices	33
5.3	Role of Community Engagement and Education in Promoting Sustainability in Makerspaces	35
5.4	Setting up Infrastructure to Support Sustainable Practices	37
6	Conclusions	40
	Bibliography	41

Chapter 1: Introduction

Makerspaces popularized the idea of personal fabrication and small-scale manufacturing, becoming widespread in public spaces, universities, and educational institutions such as libraries and schools. Makers engage in personal fabrication for diverse reasons, ranging from hobbies to research and entrepreneurial ventures. However, these fabrication processes, which rely on machines and materials, often result in the generation of waste in several different forms. Unfortunately, a significant portion of this waste is either poorly managed or not fully utilized. The rapid expansion of personal fabrication, with almost 100 percent year-on-year growth in the number of maker spaces [23] in the last decade, has sparked concerns regarding the sustainability of these processes with several researchers anticipating the environmental sustainability of personal fabrication [23, 24, 35]. Major waste is in the form of plastics (like PLA, PETG), plywood, and electronic waste which can have hazardous impacts on the environment like soil contamination, microplastic contamination, or marine pollution. According to research, almost 33 percent of all 3D prints go to waste [32] and the most common 3D printing plastics like PLA and ABS take as long as 1000 years to decompose in a landfill. Similarly, e-waste can take thousands of years to degrade as well, and some components made of metals, may remain intact in the environment forever. The environmentally harmful nature of generated waste, raises concern and makes it necessary for us to investigate ways to promote more sustainable practices in makerspaces.

To address the growing concerns around sustainability and personal fabrication, re-

searchers have pursued various approaches to address them. The concept of Sustainable Interaction Design (SID) [4] initially proposed that sustainability should be central to interaction design. Subsequently, the HCI community has conducted extensive research on sustainability, including ethnographic studies looking into making with resource scarcity and future unmaking ability in mind [10, 19], the development of environmentally friendly prototyping materials [22, 26, 34], innovative approaches to reuse, recycle, and repair [16, 20, 28] as well as 'unmaking' [33] [19]. There exists a gap in comprehensive studies that investigate existing practices in making and challenges in sustainable making while considering the viewpoints of all stakeholders in the ecosystem, including both makers and managers.

To bridge this gap, we conducted a qualitative study based in the United States. This involved conducting in-depth semi-structured interviews with a diverse group of 15 individuals, including makers who had different roles like researchers, hobbyists or entrepreneurs and maker space managers. Additionally, we conducted on-site visits to maker spaces to observe their functioning and gain a first-hand understanding of their operations, machinery, techniques, and processes in context to sustainability. Based on first-hand accounts of individuals involved in personal fabrication within maker spaces, spanning contexts like research, entrepreneurship, and hobbyist pursuits, the research provides findings about making practices and contributing factors leading to sustainable as well as unsustainable behavior within maker spaces. This in-depth study investigates and analyses - the processes individuals undertake before beginning projects, selection of materials, considerations during the selection, prototyping methods, post-completion traditions, and waste management. It offers insights into the perspectives of both makers and maker space managers, shedding light on opportunities and obstacles in achieving sustainability. Furthermore, it uncovers indirect factors contributing to unsustainable behavior, such as design and prototyping practices, lack of resources, lack of knowledge, and lack of motivation and incentive to name a

few. The main contribution of this work is the formulation of actionable recommendations based on these findings to guide future efforts in promoting the adoption of sustainable practices in personal fabrication. These recommendations advocate prioritizing sustainability in the design phase, streamlining the adoption of sustainable approaches, educating makers through training and community engagement, and establishing infrastructure to facilitate conscientious waste management and resource optimization.

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Chapter 2: Related Work

2.1 Sustainable Fabrication Technologies

A growing body of research has explored sustainable approaches to personal fabrication and making. One major area focuses on developing environmentally friendly materials as alternatives to conventional plastics and foams used in 3D printing and other prototyping processes. Wall et al. [39] introduced a method to reuse 3D printed objects as infill material for new prints, reducing plastic waste. Spent coffee grounds [29] and various bioplastics [3, 37] have been investigated as sustainable feedstocks. Mycelium composites have been used for digitally fabricating objects and embedding electronics instead of plastic enclosures [36]. Other biodegradable materials like biofoams have also been explored [25].

In addition to sustainable materials, researchers have developed design strategies and workflows intended to promote reuse, repair, and minimizing waste. Novel "unmaking" methods allow designing objects for future disassembly and component reuse [30, 33, 41]. Design for repair [16, 27, 43] and designing with waste streams [7, 9, 38] are other complementary approaches. In the case of electronics, work has looked at decomposable [34] and even edible circuit elements [22] to reduce e-waste, as well as up-cycling broken devices into new products like e-ink displays [15].

Beyond technological innovations, qualitative research has examined sustainable practices in diverse settings. Ethnographic studies at e-waste sites in Australia identified op-

opportunities for "unmaking" in the HCI community [19]. Interviews with digital fabrication experts highlighted the potential of biomaterials like mycelium [26]. Participatory design activities have explored the concept of "salvage fabrication" - making new objects by reusing and repurposing materials while considering their origins and destinations [10]. In a dedicated workshop [42], researchers collaborated to identify potential HCI research directions, specifically aiming to cultivate a more sustainable "making" environment within and beyond laboratory settings.

Despite this prior work, there remains a lack of in-depth understanding about how sustainable making methods and materials are actually being used in real-world settings like makerspaces, labs, and entrepreneurial spaces. Identifying barriers to widespread adoption and mapping the current landscape of sustainability practices among makers is an important challenge. Our work aims to highlight these knowledge gaps and guide future work in building sustainable personal fabrication technologies.

2.2 Approaches for Promoting Sustainable Practices

In our previous discussion, we delved into personal fabrication technologies that aid in sustainable making practices. However, it is essential to recognize that sustainability challenges are complex and consider options beyond technological solutions. This section aims to shed light on topics like design methodologies and behavioral interventions that can contribute to the pursuit of sustainability within personal fabrication spaces such as makerspaces.

The field of Sustainable Human-Computer Interaction (SHCI) has evolved to tackle sustainability from a multitude of perspectives, recognizing the intricate interplay between design decisions, human behavior, and environmental impact. Sustainable Interaction Design (SID) [4] pioneered the integration of environmental considerations and human behavioral

factors into the design process of interactive technologies. Researchers have undertaken efforts to analyse design decisions across a spectrum of sustainability-focused projects, proposing frameworks such as the "Should do, Can do, Can know" model [40] to guide design choices. Furthermore, the SHCI community has dedicated significant attention to the development of design patterns, principles, and strategies [21] that emphasise the impact of the design process on sustainability outcomes. These efforts aim to establish a comprehensive repository of best practices, serving as a valuable resource for designers and practitioners alike.

Behavior change interventions have also emerged as a potent tool in the pursuit of sustainability within SHCI. Researchers have explored the potential of sensing and data visualization techniques [2, 6, 8, 14] to encourage responsible actions, particularly in domains such as energy consumption. Within this, studies have investigated the leveraging of digital mobile technologies [12, 13, 18] to facilitate self-reflection and provide eco-feedback, fostering sustainable behaviors through increased awareness and engagement. While the areas mentioned do not encompass the entirety of SHCI research, they exemplify the diverse range of topics and approaches being explored by HCI researchers to address sustainability challenges. As personal fabrication spaces like makerspaces continue to gain prominence, design decisions, analysis, behavior change interventions, and educational initiatives will play a pivotal role in cultivating sustainable practices within these creative environments.

Chapter 3: Methods

The aim of the research was to investigate the methods and approaches used by makers and managers, with a focus on sustainability. We opted for semi-structured interviews as this method enables us to guide the conversation in line with our research objectives while still allowing for open dialogue. We conducted semi-structured interviews with 15 participants. Participation in our study was voluntary and the study protocol was approved by the Institutional Review Board at the institution.

3.1 Recruitment

To recruit the participants we used a combination of purposive and convenience sampling. An eligibility criteria was established to recruit suitable participants. Eligible participants had to be makers with at least two years of experience in hardware prototyping. Their prior projects and experience provided insights into their workflow, offering valuable data for analysis. A total of 15 participants were recruited. All participants shared a common identity as makers, but they had diverse roles, including Researchers, Makerspace members, Makerspace managers, Lab managers, Hobbyists, or a combination of these roles. Purposive sampling was predominantly used to recruit researchers from the our networks leveraging contacts in the research community. They were directly contacted and briefed about the study requirements. Given the proximity to public makerspaces, convenience sampling was used to recruit participants from public makerspaces. We made

recurrent visits to several different maker spaces and also put up recruitment advertisements in makerspace mailing lists. Interested participants were reached out for further communication and recruitment. To build rapport with makerspace managers and makers, we introduced ourselves as fellow makers during visits to their makerspaces and participated in their events before conducting the interviews. This allowed us to become part of their community and ask focused and informed questions about their maker activities during the interviews. Refer to Table 3.1 for a comprehensive overview of the participants’ demographic details.

Participants	Role	Work space	Experience
P1	Researcher	Research Lab	5-10 years
P2	Makerspace member	Public Makerspace	10+ years
P3	Makerspace manager	University Makerspace	10+ years
P4	Researcher	Research Lab	2-5 years
P5	Makerspace manager	Public Makerspace	10+ years
P6	Researcher	Research Lab	2-5 years
P7	Makerspace member	Public Makerspace	5-10 years
P8	Researcher	Research Lab	2-5 years
P9	Researcher	Research Lab	2-5 years
P10	Makerspace member	Personal Makerspace	10+ years
P11	Makerspace member	Public Makerspace	10+ years
P12	Researcher & Lab manager	Research Lab	5-10 years
P13	Hobbyist & Makerspace manager	Personal Workspace	5-10 years
P14	Student maker	University Makerspace	2-5 years
P15	Student maker	University Makerspace	2-5 years

Table 3.1: Participant demographic data

3.2 Research Studies

Semi-structured interviews were conducted with the 15 participants [Table 3.1]. We conducted interviews through a combination of in-person meetings during onsite visits and remote sessions using the video-conferencing tool Zoom. Additionally, we carried out on-site observations in conjunction with these interviews during our visits. Each interview had

an approximate duration of 120 minutes, and participants were compensated at a rate of 20 USD per hour. We conducted the interviews to gain insights into the participants' making practices. The primary goal was to understand both sustainable and unsustainable practices within their creative processes. To tailor our questions appropriately, we adjusted the interview questionnaires based on the specific roles of the participants. For academic researchers and maker space members, the questionnaires covered topics such as their design processes, iteration methods, materials usage, collaboration processes, challenges faced, sustainability practices and final outcomes. These interviews often delved deeply into the participants' work to explore their processes. For maker space managers and lab managers, we included additional questions related to their management strategies and the challenges they encountered in overseeing spaces. All interviews were recorded and later transcribed. These transcripts served as the basis for further data analysis.

3.3 Data Analysis

We extracted 25 hours of interview data from the recordings, which were then transcribed for further analysis. Using inductive thematic analysis [31], all the collaborators engaged in multiple rounds of open coding without any predetermined codes. Codes were generated freely throughout the analysis process. We consistently met to review emerging codes, create a codebook, and make continuous updates. The code generation continued until no more new codes emerged from all the interview transcripts. Once we saturated generating new codes over several iterations, the effort culminated in a final codebook comprising 29 codes. These codes were subsequently organized into a hierarchical structure of themes, and a consensus was reached regarding the overarching findings, which will be discussed below.

3.4 Positionality Statement

The author is a member of a research lab focused on interactive technologies and proficient in hardware prototyping methods to accomplish our research objectives. We also identify strongly with the maker community. Reflecting on our own work and practices as makers, we were motivated to contribute to the promotion and integration of sustainable practices within the maker community. The author with an educational background in Electronics Engineering and Human-Computer Interaction (HCI), specializes in qualitative research methods. These variations helped in having different perspectives about research methodologies. Hands-on involvement in making provides us with valuable insights and an intimate understanding of the processes involved. This firsthand experience proved instrumental in crafting the interviews and analyzing the data, enabling us to extract meaningful insights from the research.

Chapter 4: Findings

In this section, we elaborate on three aspects of our findings to provide a comprehensive view of how waste is produced, handled, and processed—before, during, and after the stages of making and prototyping.

4.1 Types of Waste: Those Wasteful and Those Still Usable

Drawing from interviews with practitioners across diverse specializations and on-site observations, we uncovered two common types of wastes: material waste produced as byproduct during various machining processes in making, and artifacts, intermediate prototypes, and archived projects that may still be functional but are not in use.

4.1.1 Material waste produced via various machining

All participants identified processed raw material, created through making and prototyping, as a significant source of waste. For example, a common type of waste observed across all the sites we visited involves plastics like PLA, ABS, and PETG from Fused Filament Fabrication (FFF) 3D printing. As the most widely-used rapid prototyping machines in makerspaces and research labs, FFF 3D printers are “*pretty much at the heart of any project where you’re making a physical prototype.*” Their inherent bottom-up printing process requires the generation of support structures, which become waste once the printing is complete. Additionally, failures in FFF 3D printing are very common and can result in a

great amount of plastic waste.

You see a lot of the prints we were doing were not these little baby prints we were doing you know 20-28 hour prints and we'll kick a print off before we leave for the evening. And just let it roll all night and we need it to work and if we had a problem or like suddenly 20-30 percent of our prints were failing, that's a problem. We have to do the whole 20hr print again. [P10-makerspace-member]

In addition to 3D printing, subtractive manufacturing methods like CNC machining and laser cutting are also popular at the sites we visited. Both types of machines create shapes by removing material from sheet materials such as wood, acrylic, or thin metal, and the leftovers become a major source of waste. In the case of CNC machining, the sawdust generated during woodworking jobs is often considered a difficult byproduct waste to manage. For laser cutting, the corner pieces of a sheet of material are frequently discarded. P7 stated:

So, the one thing that I think is most wasteful in my shop is when I do acrylic prototyping using lasers to cut the acrylic. There's no way to recycle it, so you try to use as much of it as you can. Eventually, the corner pieces get too small to be useful for anything, and they're just not viable. [P7-makerspace-manager]

A final category of by-product waste that we uncovered includes chemical solutions used in either the pre- or post-processing of certain materials. Examples include the alcohol used for cleaning 3D-printed models made of resin, and the liquid used in desktop waterjet cutters.

4.1.2 Brand-new components, intermediate prototypes, and archived projects

While byproducts generated through machining are mostly wasteful, participants noted that functional components and prototypes can also become waste. These include brand-new components purchased before the start of a project to test new approaches—these may become unnecessary if the project’s direction changes; intermediate prototypes created during the making and design process to verify specific features—these are no longer needed after testing; and finished projects that are not being maintained and thus become obsolete.

P10 showed us a few brand-new custom PCB boards. These boards are put in a small cardboard box next to his working desk as where he “*put parts that not needed*”:

I designed these PCB boards for this robot project because I needed them to be small and breadboard is too big. These PCBs are made by another manufacturer, but all these companies have a minimum order for PCBs. So, I ordered 10 of them and used 2 to test the design. The remaining 8 are still good, but now I don’t need them. [P10-lab-member]

Similarly, P9 reported how he often orders what he needs during prototyping, but does not revisit them afterward:

I usually buy different parts during prototyping because I don’t know which one works. I need to do my experiment. If they don’t work out, you’re like, ‘Okay, returning it is too much work, so I guess I’ll just keep it here.’ And then nobody uses it, right? It ends up being a waste of money and it takes up space. Eventually, you’re like, ‘Okay, let’s either toss this or give it away.’ [P9-lab-member]

At one makerspace, we observed a wall filled with project storage boxes, most of which were already occupied. P3 discussed how the space is utilized:

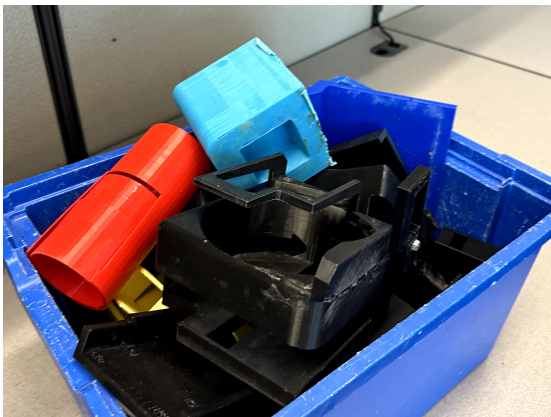
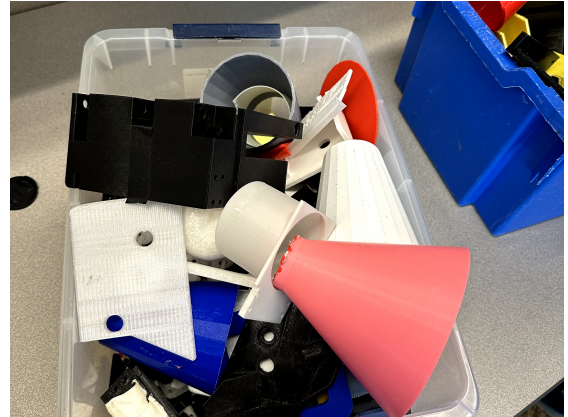


Figure 4.1: (A) Organized collection of beer caps repurposed into various products; (B) Repurposed filament boxes transformed into labeled component shelves; (C) A precisely organized and labeled rack from a community makerspace; (D) Electronics waste including chargers, CPUs, machines etc.

These storage boxes are designed for members to put their ongoing projects in. You know, a lot of these projects take a long time to complete, so people need places to store them. But some of these boxes have been sitting here for a long time, and we don't really know if the projects inside are finished or unfinished. I don't want to throw away anyone's project before confirming with them, so for now, they're still here. But eventually they may just become trash.

[P3-makerspace-manager]

4.2 Handling Waste: Trashing, Keeping, and Reusing

Participants discussed various ways of handling waste generated in making and prototyping.

4.2.1 “They are all going to the trash bin.”

Most machining byproducts and daily consumables, whether potentially recyclable or not, are directly discarded, making up a large portion of the overall waste. At several sites, we observed large trash bins installed within the space. Material scraps, such as corner pieces of acrylic or support structures from 3D printing [Fig. ??], are thrown directly into these bins.

We wanted to have a record of all our 3D printed iterations and what we did and what happened, we would just take them all out, set them on a table nicely organized, and what versions they were in whatever, take some pictures just for like a visual record. And then they all go in the trash, because we had buckets and buckets and buckets of this stuff. I mean, you can imagine what prints from 40,000 kilometers of filament would look like . [P10-makerspace-member]

It should be noted that not all 3D printing materials are the same from a recycling standpoint. PLA and PETG, two of the most commonly used 3D printing plastic filaments, are easier to recycle than other materials such as ABS. However, a majority of participants have confirmed with us that all plastic materials are treated the same. They are not sorted by type during 3D printing, nor are they handled separately after printing is complete. Instead, they are indiscriminately discarded in the same trash bin. One lab managers P11 commented about this:

You can recycle PETG filament, but most places won't take it. And I try not to be that person who throws everything into the recycling bin to let them sort out. I think it's very few places that will actually recycle PETG parts, because they don't know what kind of plastic it is.[P11-makerspace-member]

Besides 3D printing wastes, scraps from CNC are also handled in the same manner, although some scraps may be more recyclable than others. P8 talked about CNC waste being disposed off directly in the trash because the CNC shop is used by a diverse group of people working with various materials. It's hard to sort out a mixture of small pieces made of different materials. She mentioned:

In the CNC shop, we have this rule where everyone has to vacuum after they finish their job. but the suction isn't 100% efficient, you know? There are always bits lying around. It's just basic cleaning stuff. But I think all that waste just ends up in the landfill because you can't really recycle it. Mixing different materials makes it hard to recycle. [P8-lab-member]

The last group of waste that we identified as being thrown away consists of components or prototypes that are still functioning. It's worth noting that not all prototypes end up in the trash bin. As we will explain in Section 4.2.2, a number of makers choose to keep as many prototypes as possible with them, or until their storage reaches its capacity. However, we also found that at different cases, makers and researchers may directly throw functional components, or even prototypes away. In one example, P6 discussed the early assembly he made for his research, which involved metal components such as bolts and nuts to put two 3D printed shells together with wires and a few LEDs embedded. The entire assembly was thrown away in a trash bin without being disassembled:

I know it has small bolts and nuts, and also wires. Now that when you ask, it's

better to remove them from the plastic before trashing them. But most of the time, I don't think about it but just throw them all together. [P6-lab-member]

4.2.2 “I wish I could keep them all.”

For finished projects and large intermediate prototypes, storing them on site seems to be a common practice. Several participants reported that they keep all their project iterations and intermediate prototypes even after the project has ended. For them, these iterations signify the hard work that went into the project, and they would like to have a memory of it. P7 said:

I keep them as long as I can bring myself to do so. I also number all my prototypes. Sometimes, it's nice to look at all of them. [P7-makerspace-member]

P1 also expressed similar sentiment. When asking about how he handle the prototypes he developed, P1 said:

I kept some prototypes for the very reason, to have them on my desk, because they were nice. And this was all my blood, sweat, and tears in there. [P1-lab-researcher]

Besides archiving finished projects for documentation purposes, participants also mentioned that they may store items in the hope of using them someday. They reported keeping various intermediate prototypes and broken machines, in hopes of salvaging hardware or spare parts as needed in the future. P6 said:

It depends on whether we can scavenge parts from it. So for example, we have this color thermal printer that we bought off eBay. It's broken and doesn't work, but we keep it around because we think there might be some interesting components in it. [P6-makerspace-manager]

From the interviews, it became evident that participants tend to stop storing items or dispose off stored projects only when they run out of space. *“If it were up to me, I would store everything I ever make, but only if I had that much space.”* When the amount of stored items exceeds the available space, it leads to a deep cleaning. Lab members or makerspace members will quickly sift through the parts. Since the primary goal is to free up space, this cleaning process can be rushed, and parts that were saved for future use may eventually end up in the trash bin.

P7, who tent to keep all his prototypes, admitted that this can be very challenging. When talking about the prototypes that he currently has, he said:

I mentioned being on the 35th revision of this project, but I don't actually have 35 of them. There is no space for me to keep all of them so some are gone during cleaning. I have about 5 left, 5 major iterations that represent successful key stages of the project. [P7-makerspace-member]

4.2.3 “The motor got three more lives.”

While a great amount of waste is discarded, we did come across a few unique approaches that practitioners have employed to find new uses for the wastes.

P6, who works in a well-equipped university lab, discussed their university’s practice of directly recycling PLA filament, in contrast to most places we discussed previously. In his lab, they have a strict rule that only allows the use of certain brands of PLA. After printing, all the PLA scraps must be sorted by color then being send to on-site, centralized professional recycling equipment to be re-extruded into new filament that can be used again. Because sorting the plastic and maintaining the equipment is complicated, they have assigned dedicated employees to manage the recycling process.

It's really nice that we can recycle PLA, but it really took them a long time to

get to a consistent process, even with the setup they already have. They also need to do regular maintenance, like taking out the nozzle, bringing it to the workshop, and hitting it with a blowtorch just to burn off all the PLA. Then they clean the nozzle and put it back in. This is something they have to do every couple of weeks. The whole recycling process, it's taken them about a year to fine-tune it and get to a point where they can make consistent filament from just PLA, nothing else. [P6-lab-member]

As is evident, recycling PLA is currently a resource-intensive process, and only a few facilities, at best, may have the capability to implement it.

While recycling material scraps systematically is not an affordable option, there are makers who have attempted to make at least partial use of these scraps to create new projects. As one example, P10 once converted 3D printed waste found from his site into an art piece that he was very proud of:

These waste is from my work, and I tried to convert them into some art pieces. So, for example, in my own home, I created a small transparent bag and filled it with failed 3D printed materials. Next to the bag, I think I labeled a packet and printed something on it, and the whole thing will be like a poster. It's a 3d poster. And I hang it on my wall. [P12-lab-manager]

P11 shares a similar sentiment about turning material waste into art pieces. He considers himself both a maker and an entrepreneur, specializing in making coasters from beer caps and cans. He discussed his plans to create art from metals like bottle caps and cans:

I've got boxes full of them, and I'll probably end up recycling them. They have lots of cool colors and are pretty much all the same. I'm thinking of making a mosaic out of them. [P11-makerspace-maker]

Apart from managing material waste, makers and practitioners have more experience and willingness to repurpose or reuse still-functional components. This is especially true if the components have a relatively high value or are otherwise difficult to find. P10 shared a story with us about how he salvaged a fully functional motor from a broken machine and repurposed it in different projects:

I had a window regulator in my car that went bad. You know, I had to buy a new one cause the pulley was all messed up. But the motor was awesome, so I saved it. Two years later, it ended up in a gantry [of a DIY robot]. And then, as the robot grew, it wasn't big enough for that anymore. So that same motor got repurposed into something to spin a rotary test tool we're using. So yeah, that motor that came out of a car actually had three more lives after the car.

[P10-makerspace-member]

As mentioned earlier in Section 4.1.2, intermediate prototypes and even finished projects may end up gathering dust on a shelf. At some sites, managers and members make extra effort to disassemble them and reuse their parts. P5, a makerspace manager, mentioned how the high school robotics team, who are their members, improvises on their robot every year to meet the requirements of new design challenges:

They don't keep all the robots. They dismantle the previous one and use the same motors from the old one to build a new one. I also dismantle things that I know no one will use. If somebody needs an Arduino, I'm not going to buy a new one; I'll give them one I found from an old project. [P5-makerspace-manager]

Functional components may also circulate within the local community. P5 reported that almost all of the things in their space were donations by “*scientist and friends*”, including

3d printers, CNC machines, sensors etc. Not all donations work as they showed up, but P5 has hosted several workshop called “*Fix it and its yours*” to “*giving them a new life*”:

Often times people end up buying personal 3D printers and when it stops working smoothly they get super frustrated and end up giving it to our maker space. Sometimes when I have such machines in the space I arrange something called ‘Fix it and its yours’. Anyone who fixes the machine first gets to keep it. This way the machines don’t go out of use. We find them new home.

[P5-makerspace-manager]

4.3 Challenges in being sustainable

All participants in our study recognized the significance of sustainable making but found it challenging to apply sustainable practices in their work. Through our interviews, many expressed concerns about frequently producing material waste. “*I feel guilty about all the wood I use and waste in the process, so I try to plant trees equivalent to my usage*”. However, we note that embedding the notion of sustainable making into daily making and research activities can be challenging for three main reasons: the lack of appropriate processes and equipment for handling waste material, the high cost associated with sustainable practices, and the missing know-how.

4.3.1 Lack of procedures and equipment

Many participants discussed their attempts or intentions to be more sustainable, such as by trying to recycle printed plastic themselves. However, they cited a lack of practical guidance and tools within the community as obstacles to doing so. For example, during our visit to P3’s cite. He referred to an entire pile of plywood and said:

We use large amounts of plywood in the woodshop. And those are frustrating for us because I don't have a good recycling solution. All these sawdusts generated through CNC or laser cutting. We've talked to different people on campus, we've asked amongst other university makerspaces what ideas they have. We haven't really gotten very far with it. [P3-Makerspace-Manager]

Same concerns are seen on how printed plastic cannot be recycled. P3 showed us their efforts to convert 3D printed waste into molds so that they could be reused. However, the entire process requires P3 to have a specialized device to melt or dissolve the plastic and then prepare a separate mold each time. The process is not streamlined; and due to the need for careful temperature control during the melting phase, they haven't achieved completely satisfied results. P11 shared similar concern. When talking about the daily waste produced through 3D printing process, P11 commented:

That's a lot of plastic. I really don't want to throw them away if I can have a way of using them, but there's not much you can do with with scrap 3d printed parts. Unless, I mean, you've got to have, like I was saying, gotta have a grinder and an extruder turn it back into usable filament. But these are not like the cheap printer that you can just buy.[P11-makerspace-member]

The grinder and the extruder that P11 referred to are specialized devices capable of breaking down 3D printed plastic parts into smaller pellets, which can then be melt, and remade into new filament. As discussed earlier in Section 4.2.3, a very few well-equipped makerspaces may have access to such machines. However, compared to the overall number of makers or the prevalence of 3D printing services within these makerspaces, these devices are not accessible to the majority.

4.3.2 Sustainable actions may not be worth it

The cost of sustainable actions is another practical reason why makers and researchers don't always give them the priority when making decisions. Being more sustainable often requires extra steps, additional labor, or increased expenses, all of which can pose a burden for many.

For example, properly disassembling an intermediate prototype is a reasonable approach for reclaiming functional components, as we have identified in Section 4.2.3. However, in practice, the process may be demanding, as it may require pausing and interrupting ongoing design iterations, and dedicate time and effort just to unscrewing different parts or desoldering electronics from an old board. people may choose to recycle components only when they consider it worthwhile. P8 said:

I think we try to balance between the time we spent on, like recycling or any of that, versus the actual research outcome. So, as a research lab, our times are valuable. Being more sustainable is not one of our brand, so if throwing away a very cheap thing is gonna save you a lot of time on research, then just do it.

[P8-lab-member]

Makerspace managers resonate. When asked about how they decide what to disassemble or reuse, P10 responded:

Depending on their value. But the screws? Typically not. Because we can buy a box of 100 screws for like \$4. It's just way easier to buy new ones than spend more time or hire someone to dismantle and reuse existing ones.

[P10-Makerspace-Manager]

Similarly, P7 who used to collect an extensive amount of metal chips for his own project, commented on why he didn't want to bring them to a dedicated recycle facility:

I'm not gonna get any money for this from the scrap yard. It's literally not worth my gas to get there and get back. And I don't want to damage the planet. I'm doing in my opinion worse by just wasting gas. [P7-Makerspace-Member]

4.3.3 Knowledge gap

One additional concern is the insufficient level of knowledge and understanding about sustainability. The democratization of digital fabrication tools has made design and prototyping more accessible than ever. However, individuals new to the field of making may not possess an understanding of appropriate methods for material handling or waste management. For example, at one site we visited, we observed a member of the site improperly disposing of isopropyl alcohol—used for washing resin printed parts—by pouring it directly into the on-site sink. The individual was unaware of the issue until we pointed it out. P5 indicated:

Whenever someone is dealing with things incorrectly, and someone who knows about it would try to point it out. But I think like things definitely slip under the radar. And it's difficult to keep track of all of this. [P5-Makerspace-Manager]

P3, who has been a full-time makerspace manager for several years, reported the same difficulty of passing on the knowledge of recycling:

One of the overall more general problems at a makerspace is people see a recycling bin, and they think they can put anything plastic in the recycling bin, right? Even though our recycling bins are pretty well labeled for what's supposed to go in there. And I have to constantly remind them, if it doesn't have a recycling stream number on the bottom, you don't put it in there. [P3-Makerspace-Manager]

In other cases, the missing knowledge of handle material or components may also discourage the actions of recycling. For example, makers may hope to recycle electronic components but may not possess the required skills or knowledge to do so. P6, an expert electronic engineer, observes:

Sometimes if things are soldered, for instance, a motor was soldered, right? So in this case, if we want to reuse the motor our only option is to de-solder it, but not everyone in the lab knows how to de-solder. So a lot of times people do just buy new things because they don't know how to de-solder.[P6-lab-member]

4.4 Achieving Sustainable Making Through Implicit Means

While we have so far discussed the types of waste, current handling practices, and the challenges of maintaining a sustainable making process, we should note that there are also existing, common practices that directly contribute to more sustainable ways of making—even if sustainability is not the primary goal. We argue that these practices are easily adaptable and should be encouraged community-wide.

4.4.1 Reducing design iteration

Almost all the participants talked about how their projects require design iterations and prototyping. These processes naturally generate a number of intermediate prototypes, which, as explained in Section 4.1.2, are a natural source of waste. Thus, reducing the number of design iterations or using fewer prototypes without diminishing the design goal will lead to less material use, fewer physical artifacts on the shelf, and more sustainable actions.

In our interviews, several participants discussed their practices on reducing trial-and-errors, printing smaller parts for testing, or reusing the same prototypes multiple times as

a way for time saving. For example, P1 talked about how he uses design software and simulation to reduce the need of making multiple physical prototype:

We would have had more tries without the simulations. I can't really say like, how much of an increase that would have off the top of my head. But I am confident that it will be way more iterations that we actually had to do. [P1-lab-member]

P12, among several other participants, talked about utilize partial printing, rather than a printing of an entire model, to validate his design:

For the prismatic joint, we need to test out the tolerance inside the joints. I just print out the joint itself. I don't print the rest and I just test out this, the joints. It saves time this way. Print the entire thing will take much longer and I only need to test part of it so this is more effective. [P12-lab-manager]

In a similar vein, P6 talked about how 3D modeling and planning before making the physical prototype will reduce the mistakes for him:

For 3D printing, a lot of thinking will happen during the 3d design process. If I put more thought in the design, it will hopefully leads to less problems later on. I don't want to reprint the same thing just to fix small errors. [P6-lab-member]

While saving materials and reducing component use may not be the primary consideration for all participants during the design and prototyping process, the fact that multiple participants, especially those with extensive design experience, tend to reduce the number of design iterations and reuse the same prototype contributes to practical methods of sustainable production.



Figure 4.2: (A) Organized collection of beer caps repurposed into various products; (B) Repurposed filament boxes transformed into labeled component shelves; (C) A precisely organized and labeled rack from a community makerspac.

4.4.2 Better organization

I think one thing that makes a huge difference on whether things are put back and like reused or not, is how organized things are and how sensitive the components are. So if there is a definite place for something to go, like people are more likely to, you know, like, once they unplug it, people are more likely to put it into the workplace.[P6-lab-member]

Several subtractive processes like laser cutting or CNC machines generate left overs

like cut out pieces of wood sheets, acrylics or metal. These cut-outs are very well usable by others. We observed spaces setting designated spots to put these left over materials for others to use [Fig. 4.2]. What is more important than storing these materials for reuse is making it visible and accessible to the users of the space to all users to prevent unnecessary purchases. It is also integral to be conscious of expenses, P3 spoke about how misplacing expensive tools can lead to frustrations:

Particularly with tools that's aggravating because the tools are very expensive, you know, you'll eventually find that piece of plywood that someone put back in the wrong place, and you can always use it. But you know, I've seen places that end up with like, you know, 25, 10 millimeter wrenches. [P3-Makerspace-Manager]

Participants reported, labeling things as their go to way of organizing the space, be it tools, projects, shelves or consumables. Labeling things helps people find it even though they were not necessarily the one who put it there. One of the makerspace managers reported having dedicatedly labeled shelves and also a instruction sheet explaining the labels in further detail. P3 had a unique way of labeling things with both textual and pictorial representations:

We made this tool wall early on, this is one of the first things we did when I first came here, you know, we had these toolboxes, these tools. And I thought, well, that's we'll just put all the tools in those and we'll label the drawers. That'll work. And the volunteer students at the time said, Well, you know, that's kind of frustrating for us, because we don't really, you know, we'll look at the label that says whatever reciprocating saw, and what's a reciprocating saw all these saws reciprocate, right? So instead, we decided that we would

do these tool boards where, you know, there's a picture of the tool behind it.

[P3-Makerspace-Manager]

In another example, P8 mentioned that inexpensive, small components like jumper wires are effectively reused in their lab due to good organization.

Surprisingly, so like everything is labeled every drawer has like a function. So there's a drawer for jumper wires that we have. So like it'll just go into that drawer and like people pick it up. [P8-Lab-Reseacher]

Labeling not only helped folks in keeping track of resources and effectively finding things when necessary but also in version control of prototypes. Design process is non-linear you always circle back and forth, it is important to look back at things at times. P1 spoke about it by saying:

So, like if I had a prototype, for example, for AirTouch, that had a 3.2-millimeter increase in each of the outlets, instead of me just guessing and printing, I would either design a label to be printed with the prototype or simply write with a Sharpie immediately after it's done. [P6-lab-member]

Chapter 5: Discussions

In the preceding section we documented the findings from the interviews we conducted with the different participants in our study. In this section we discuss some actionable recommendations that could help in promoting sustainable practices in makerspaces.

5.1 Putting Sustainability at the Forefront of Design Processes

The design process in personal fabrication involves an iterative cycle of ideation and execution, with makers continuously going back and forth, making design decisions throughout. This process encompasses all steps from conceptualization to execution. Sustainable Interaction Design [4] emphasizes the importance of sustainability being at the forefront of the design process. However, our studies have found that makers often overlook sustainability considerations. In this section we want to emphasize on the importance of imbuing sustainability in maker's design process at each step, mainly: prototyping, material choices and design decisions.

To begin with, translating an idea to a tangible working output involves several in between steps like low-fidelity prototyping and 3D modeling using digital tools. While the iterative design approach is valuable for problem-solving and improvement, excessive iteration can lead to waste, as many intermediate prototypes are not reused or recycled. To address this, it is crucial to be mindful of how much is produced during iterations. The number of iterations can be reduced through proper design practices, such as low-fidelity

prototyping or spending more time refining CAD models. Our findings reveal alternative prototyping approaches implemented by participants, aimed at limiting the production of numerous prototypes, proving to be sustainable and efficient in terms of time. These strategies include adopting incremental development rather than constructing the entire prototype at once, which allows for early error detection and avoids having to recreate the whole thing. It is important for makers to consider if their approach leads to unnecessary iterations.

In addition to following the right modeling and low-fidelity methods to reduce errors, it is equally important to use materials that cause the least harm to the environment while serving the desired purpose. Empirical evidence shows a significant reliance on non-biodegradable materials like foam or plastic during prototyping, with only 23 percent undergoing recycling[26]. However, research suggests that when presented with sustainable alternatives like mycelium that serve their needs, makers are generally willing to adopt them [26]. In our interviews, makers highlighted that material choices are mostly guided by the specific requirements of the project as well as availability and affordability. This indicates that increasing access to and knowledge of sustainable options could make sustainability considerations more prevalent in material choices.

The design of a product also largely impacts the ability to reuse it after it has served its purpose or has broken down. Most intermediate and final prototypes are not reused or recycled, as they are not easy to disassemble without specialized tools or skills. Similarly, commercially manufactured items are often not designed for easy repair, contributing to a shorter lifespan. A major reason products are difficult to repair, reuse, or disassemble is that they are not designed with those factors in mind from the outset. A participant who managed a makerspace oversaw a kids' robotics team that utilized the space annually to prepare for a competition. Each year, the team repurposed components from the previous year's robot, fostering an awareness of designing with the intent that future teams would

inherit and reuse their parts. Alternatively, they might only need to replace specific components as they iteratively enhanced their robots. This practice highlighted the potential to streamline processes aimed at extending product lifespans by considering such design principles from the outset. Researchers have also investigated impact of design on ability to “unmake”, particularly for electronic devices [19]. Maker’s can make an effort to think about future use cases of their prototypes or the components used in their prototypes. This could guide them to design their prototypes for future reuse.

Embedding sustainability considerations throughout the design process is crucial for promoting more environmentally conscious practices in personal fabrication and making. By adopting mindful prototyping approaches that reduce excessive iterations and waste, exploring sustainable material alternatives, and intentionally designing for disassembly, reuse, and repair, makers can significantly reduce the environmental impact of their creations. The challenge at hand involves spreading this knowledge and developing a culture of sustainable practices. Managers can play an important role in encouraging these practices as well. We noted that the dynamic between makers and managers varied significantly across different types of makerspaces. In research laboratories, managers had direct influence over makers’ practices, given the clear hierarchy of authority, often assuming a mentor-mentee role. In certain entrepreneurial settings, managers frequently participated in making activities. In these spaces as well managers had direct influence on practices followed by makers, the underlying goal in most of these spaces was to be more efficient and cost effective. Conversely, in public spaces, managers had some influence over makers’ practices; however, makers tended to follow their own methods more freely, potentially due to the payment for space usage and the less firmly established authority compared to educational environments.

5.2 Developing Technologies to Streamline Sustainable Practices

Our findings highlight the challenges that makers face in implementing sustainable practices, even though they are aware of their importance. Due to the time-consuming nature of sustainable methods and the additional effort required, efficiency often takes priority over sustainability. Makers may overlook sustainability considerations unless sustainable alternatives are convenient or cost-effective. Additionally, the lack of resources in makerspaces to upcycle, reuse, or properly dispose off materials hinders the adoption of sustainable practices. In this section, we explore how digital or physical technology can support makers in adopting sustainable personal fabrication practices.

Our study revealed several problems that pose barriers to sustainable actions, which could potentially be addressed through technology and the availability of tools. One of the most common issues is the lack of knowledge about materials and their properties. It is often difficult for makers to determine which materials are recyclable and which are not. For example, within 3D printing, some plastics are recyclable while some are not. A tool that helps identify materials and informs users about their properties could be beneficial before they decide to work with it. In a different context, a similar "material-aware" tool was developed for laser cutters [11]. In addition to this, clear and accessible information about proper waste disposal processes would be helpful as some materials like ABS plastic might require special recycling services. Makers expressed concerns about wrongly disposing off non-recyclable materials in recycling bins or improperly collecting waste due to a lack of knowledge regarding the correct disposal methods. Knowing material properties can also aid in effective waste sorting, in larger makerspaces with numerous members, waste materials like failed 3D prints made of different materials are frequently discarded together, making it difficult to identify and separate the various materials for proper disposal. Even in spaces with proper recycling infrastructure in place, they reported needing

designated people to make sure material is sorted by material type as well as colour in case of plastics. Technology for easy identification of material and to guide in disposal could help streamlining this process.

Conscious material choices are crucial, but it is also important to reduce the amount of waste created during the making process. The right design practices can help in this regard. At the same time, machines and tools can also contribute to waste reduction. A participant who was an entrepreneur, highlighted the challenge of running lengthy prints that consume substantial material, where any errors result in the loss of both time and resources invested in the failed print. Early identification of errors holds the potential for significant savings in time and resources. Various tools are available in the market, including those designed to detect real-time 3D printing failures as the printing process starts, allowing for immediate suspension of printing upon error detection, preventing further waste. Another example involves developing plugins or add-ons for slicing tools, facilitating the selection of optimal parameters like infill percentage and other variables, tailored to functional and structural demands for efficient material utilization. An example mentioned earlier involved, designing modified 3D printers which accept failed prints as infill, to reduce the amount of material used [39].

Even with conscious material choices and efforts to minimize waste generation, some waste will inevitably be produced. Numerous participants were unaware of the existence of machines designed to facilitate better waste management, such as those capable of generating filament from failed 3D prints. While these machines are available, they are often expensive and therefore not widely accessible. Despite the concern over plastic waste, there is a lack of awareness and accessibility to potential solutions. Easier alternatives to recycle some of the commonly produced waste could encourage wider adaptability. One participant mentioned shredding and melting 3D prints to create a reusable tray. Supporting such small-scale interventions with appropriate machinery could facilitate waste reuse in cre-

ative forms. While reducing costs and enhancing accessibility of recycling infrastructure would be the most efficient, developing tools for smaller-scale recycling practices could be beneficial. Another crucial aspect involves salvaging prototypes or repairing broken machines, tasks that demand a certain level of skill and effort. However, users often express reluctance to invest time in manual activities like sorting screws or desoldering components for reuse. For instance, to repurpose small and inexpensive parts like screws, nuts or bolts makers must first disassemble prototypes and then meticulously sort through them to find suitable components for future projects. Yet, these additional steps are often deemed unworthy of the time investment, particularly when new screws are readily available at low cost. Automating these processes could potentially incentivize makers to embrace the reuse of smaller, affordable parts like screws.

Developing technologies that support makers can greatly simplify sustainable personal fabrication. Dew et al. [10] highlight the valuable role that tooling plays in encouraging makers to think more critically about who and what is involved in the larger networks of technology production. By providing makers with tools and streamlined methods, they are more likely to engage in sustainable actions that they may otherwise avoid due to the high effort for minimal perceived return. This discussion aims to inspire new ideas and identify opportunities where technological interventions can make a significant impact.

5.3 Role of Community Engagement and Education in Promoting Sustainability in Makerspaces

This section emphasizes the importance of enhanced education and community engagement in promoting sustainable personal fabrication practices. While makers are aware of the unsustainable nature of some of their practices, a notable gap remains in the effective implementation of sustainable practices, primarily due to a lack of knowledge among

participants. We observed that, they could take better action on their willingness to be sustainable if they were more aware of possible alternatives, processes and the resulting environmental impact.

The current practices followed by makers mostly depend on existing practices established within the makerspace by the managers. The influence of managers on individual makers' actions towards sustainability emphasises the importance of educating managers. Organizing more training sessions for managers, with an emphasis on sustainability, can facilitate the transfer of knowledge to the maker community they engage with. In addition to establishing best practices by managers, it is important for makers to individually to be knowledgeable about sustainable practices for effective implementation. There could be several ways of knowledge sharing in makerspaces. Within more established organizations, mandatory training sessions are commonplace before individuals can utilize machinery. These sessions present opportunities to incorporate sustainability-focused material and equip individuals with the necessary knowledge. Managers could also facilitate knowledge sharing through workshops or seminars. Experienced makers could share insights and strategies, helping others to explore innovative approaches that minimize environmental impact. To encourage passive learning, easily accessible material on sustainable alternatives or considerations related to the machines being used could be placed at major checkpoints within the spaces, such as near the 3D printers or laser cutters.

While direct methods like structured modules or informative sessions are effective, their implementation may be constrained by resource availability. An alternative to this could be community engagements and events. For instance, one participant highlighted the value of hosting repair and disassembly sessions within makerspaces, involving all members and community participants. People would drop off broken down machines they no longer want and anyone who successfully repairs it could own it. Similar kind of event was reported involving high school kids, with simpler tasks like sorting components or screws.

Such communal engagements not only facilitate knowledge exchange but also emphasise the importance of waste reduction and the efficient use of materials. Leveraging social practices and community engagements can promote a sustainable making culture. Other papers also talk about how social practices and community engagements can be leveraged to promote sustainable making culture[10] [19].

In addition to efforts by makers and managers, educational initiatives undertaken by machine companies can play a crucial role in facilitating unintentional learning. Common machines like 3D printers, CNC machines, and laser cutters are prevalent in all spaces. Manufacturers can contribute to sustainability by educating users about commonly used materials and proper handling methods, as well as suggesting alternative options. As we discussed earlier, makers struggle in finding the right services for disposing waste which is not commonly recycled at local recycling centres, companies can take the initiative of partnering with recycling services and passing the information with their products. Some major 3D printer manufacturing companies have started acknowledging the unsustainable nature of the materials commonly used on their machines and have started talking about alternatives and educating their users about them [5]. Although the path to mass adoption may be long, initiatives such as selling filaments made from recycled plastics signal promising steps towards sustainability[1].

5.4 Setting up Infrastructure to Support Sustainable Practices

In addition to fostering knowledge about sustainable practices, investing in infrastructure that supports sustainability is crucial. This infrastructure encompasses several crucial elements, including waste management streams such as recycling services, access to waste processing machinery like filament recycling machines, and mechanisms for sharing artifacts like machines, tools, and spare parts.

Our findings revealed that many makers and managers faced challenges in finding ways to dispose off waste responsibly. They lacked access to supporting infrastructure, such as recycling facilities or waste processing services. One participant expressed, "We are eager to find the right way of handling waste, but lack access to supporting infrastructure." While some academic labs had dedicated recycling services and even filament recycling machines, these services were often financially burdensome and required significant management and maintenance efforts to ensure smooth operation. Notably, the availability of such infrastructure influenced makers' behavior. When waste management services were in place, makers were more conscious about sorting waste into assigned categories and put more thought into ensuring conscious disposal. Conversely, the lack of these services increased negligence, as it required conscious effort and time dedication on the makers' part to ensure sustainable behavior. Access to these services should not be limited to universities and larger organizations and should be made more accessible.

In addition to proper waste disposal, having a system to share tools, machinery, equipment and spare parts within and across maker communities could greatly reduce waste and maximize resource use. We found that one type of waste was broken or old machines. Some machines and tools don't get used as much in individual makerspaces since they are underutilized when only one space or person owns them. The "Library of Things" concept proposed by Jones et al. [17] provides a model for this - a shared collection of physical items that can be borrowed. While sharing within one makerspace or university is common, extending this across multiple spaces and a wider maker network is challenging.

Widespread sharing requires more than just logistics of managing inventory and enabling transactions. It needs a mindset shift to value sharing over personal ownership. By sharing resources, makers can avoid duplicate purchases. Several makers reported that not everyone has the skills to repair machines, so when one breaks down, it sometimes gets trashed without repair. With a larger sharing network, there also would be more people

available to maintain and repair machines, preventing them from ending up as waste. A system to share tools and equipment could reduce unnecessary spending, ensure better maintenance of resources, and cut down on machine waste. Although setting up systems for sharing tools and equipment is challenging, the possible benefits of reducing waste and saving money make it really worthwhile.

Chapter 6: Conclusions

Our research investigates making practices within makerspaces from the perspective of both makers and makerspace managers. Our findings uncover the kind wastes generated in makerspaces, how the waste is handled, the challenges with sustainable making and how implicit measures lead to sustainable behaviors within maker spaces.

Our recommendations focus on integrating sustainability into design, developing user-friendly tools, bridging the knowledge gap, and fostering a culture of sustainable making. We hope this research guides future work in promoting sustainable making practices.

Any text within this document has not been generated by AI. Instead, we utilized AI tools such as ChatGPT and Claude for occasional proofreading and error checking, in addition to other tools like Grammarly.

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