Making within limits: Towards salvage fabrication

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ABSTRACT

Cultures of making have received broad attention within HCI studies of design and material production, surfacing the uneven social and political consequences of maker visions. Less explored but equally important in this scholarship is what it means to make within limits: what makers' tools would look like if they took seriously concerns for resource scarcity, provenance, and disposal. Deploying a mix of ethnographic and design methods, this paper identifies salvage practices as a core but under-recognized resource within an academic makerspace. To help open the conversation around making within limits, we propose a series of tools for salvage fabrication, an alternative design concept that emphasizes the interconnected material flows into and beyond local processes of material production.

KEYWORDS

Digital fabrication, making, salvage, repair, sustainability, craft, timber framing.

1 INTRODUCTION

Across the last decade, scholars of human-computer interaction (HCI) have carefully examined the role of making in key social, technical, and political developments. Some have suggested that emerging tools for digital fabrication help destabilize local socioeconomic hierarchies, enabling novice makers to envision procedures that revolutionize entire industries [27] or cope locally with a future of collapse [51]. Others have argued that digital fabrication increasingly hinges on the techno-optimistic promise of entrepreneurial living, positioning once peripheral cities like Shenzhen as the very center of global economic activity [48] and hiding core mechanisms of exclusion and racialization as a result. Ultimately, whether optimistic or cautious, tales of making and digital fabrication have often centered on visions of innovation — innovation for all, innovation for some by others or, mostly broadly, an innovation of displacement, shifting who and what come to matter in the present.

This paper departs momentarily from this innovation discourse to ask: what happens when we consider material scarcity and breakdown? What might we learn from not just the uptake of digital fabrication tools today but also their reliance on scant and limited resources tomorrow. For example, the ABS (acrylonitrile butadiene styrene) plastic filament used in 3D printing uses petrochemicals derived from oil hydrocarbons through energy-intensive processing. Deploying a combination of ethnographic methods and techniques of design inquiry (sketching, prototyping, and critique) [24][25][26][29][49][71], we examine and imagine the ways designers may harness concerns for resource scarcity, extraction, and reuse to expand HCI's modes of conceptualizing digital production, a process we call salvage fabrication. Salvage fabrication describes more than drawing discarded things back into use. It also highlights the way remnants of material connect up with broader ecological and industrial forces, from the railroad and sawyer networks of a past timber industry to today's makerspaces and technology production sites.

We use processes of tooling (and the conceptualization of new tooling processes) to inquire into the relationship between two sites of fabrication: one familiar to HCI as scaffolding material production in abundance (an academic makerspace) and another where material scarcity is already keenly felt (timber-framing construction site). In building connections across the two, we develop a concern for salvage fabrication that takes material flows such as PLA production and disposal as a starting point for technology innovation. For scholars of HCI and digital fabrication, this concern opens a space for seeing waste as otherwise: reworking emerging forms of technology production via tools that position marginal, displaced, and discarded materials as central and useful again. Processes like upcycling [7][72], hacking [68], and re-appropriation [74] take a discrete product or artefact as the object of an individual, creative consumer intervention. Salvage fabrication asks us to consider more radical and open-ended reworkings of what technology production and its leftovers might look like when situated in greater material and temporal frames such as the depletion of old growth forests.

2 RELATED WORK

To contextualize our interventions in digital fabrication and HCI, we first turn to the literatures that set our project in motion, beginning with a now canonical site of digital fabrication: the makerspace. Rising in popularity across the late 2000s, makerspaces became a central community-led space for informal, interdisciplinary collaboration and exploration—filled with the high-tech tools of digital fabrication and the familiar machines of woodshops, crafts rooms and art studios. As Lindtner and her co-authors observe, makerspaces are "hailed as *the* contemporary site of technological innovation" [48]. Here, makers have the resources to follow their passions, creating prototypes and eventually new products. Makerspaces are both celebrated for their entrepreneurial potential and framed as being outside the profit-driven motives of corporate mass production. Through innovation, maker citizens can develop solutions to social challenges of the present and build a better future [54].

In both academic and popular discussions, making is praised as the very activity that inspires a more responsible stance towards a consumer culture driven by buying, using and throwing away. In his book *Made By Hand*, the founding editor-in-chief of Make Magazine, Mark Fraunfelder, writes that makers have "learned how to stop depending on faceless corporations, and begin doing some of the things humans have been doing for themselves since the dawn of time." [23] When people have access to knowledge, tools and materials, they build things that they would have otherwise bought [1].

From this perspective, making reorients people to the material world—positioning them as capable of creating new things and innovations, or simply creating familiar objects in a more considered and personally satisfying way. Across scholarly conversations about making in the HCI community, a recurring theme is the potential of making to encourage more environmentally sustainable technological practices, through engaging the field in acts of repair, modification, and meaningful production [67]. These activities "create new values" for an expanding community of technology designers and producers [74].

Making draws on the self-reliant spirit of Do-It-Yourself (DIY), the make-do-and-mend ethos of crafting, and the ingenuity of hacking. Hacking, in particular, encompasses a repertoire of reuse practices. HCI field studies on hackerspaces show physical "hacks" to be alterations or modifications to existing objects or materials [68][2]. For example, in Fox's ethnography of feminist hackerspaces a central figure engages in "up-cycling" wooden pallets into fencing [21]. These lineages situate making as a natural site for material practices grounded in reusing and repurposing.

On the other hand, institutional accounts of making often center the widespread availability of digital fabrication tools and abundant materials as the driving factors of the growing number of making and makers. As Mark Hatch observes in *The Maker Manifesto* "You and I are living through the most amazing age in all human history. Materials are becoming more accessible, more sophisticated, and more fun to work with" [31].

While hopeful, these narratives depict a world of limitless expansion that loses sight of the potential for scarcity or the uneven distribution of resources. Indeed, questions of sourcing, waste, disposal, and other ecological relationships have been relatively neglected within HCI stories of material production [42]. Technology design practice increasingly entails working with resource-constrained and ecologically harmful materials like petrochemicals-based plastic filaments and the detritus of the supply networks they entail [40][41][42][58][62].

While contemporary work in technical HCI explores new materials, machines, and processes for digital fabrication (e.g. [52][53]), extending its core techniques into new domains and product applications, much of this work focuses on shortening product development cycles and to some extent reducing associated waste, such as with techniques for patching [75] and repair [85].

Complementary materialist perspectives in fabrication [10][11][12][43][57][83], craft [19][60][69][70], and design practice [39][76] demonstrate how making techniques, processes, and values are shaped by the materials and tools at hand. Posch in particular has shown how tooling, materials, and skills can be recombined to shape a new fabrication practice [60].

What happens when common materials we take for granted now become scarce? In recent years, HCI has begun to grapple with this future of scarcity [5][77][78][58] from technical, practice-based, and design-driven perspectives. Many valuable technical projects have explored the role of systems (e.g. [35]), techniques (e.g. [20]), and devices (e.g. [61]) to mitigate consumption and waste, and change consumer behavior [84]. Extending out from these technical perspectives, other scholars have turned to studies of practice to locate strategies such as reducing obsolescence, encouraging attachment (e.g. [55][56] [66]), and supporting repair to keep electronic objects longer (e.g. [5][50][50][65]. Taking a design practice lens over longer temporal frames, concepts like everyday design have been valuable for decentering the human-device nexus as the unit of intervention in sustainability efforts and expanding the temporal frame of interaction design [10][50][81][82].

In parallel to HCI's focus on sustainable design innovation, recent work has shed light on the under-examined work of maintenance and repair as alternate and equally critical modes of world-making. From Namibian ICT providers [36] to artists building with found and broken objects, [38] repair scholarship turns designers' attention towards modes of making that start with decay and breakdown rather than growth and technical progress [32][37]. In this view, materials have their own lifetimes and the human fabrication encounter is one of many that gives material its shifting qualities or propensities [13][38].

Encounters like sourcing, disposal, and waste collection bring broader material flows and their political-economic ramifications into the frame [16][18][45][46][45][46]. Tomlinson et al. argue that HCI has an opportunity to change practice through technical innovation and marketing design products [77][78]. In this view, digital technologies that help people cope with collapse in the future can be in part created by monitoring destabilizing practices (e.g. curbside farming) and technological futuring (e.g. advancing decentralized communication and manufacturing infrastructure) happening in the present [78]. In their discussion of the unsustainability of internet infrastructure and its reliance on copper and other finite resources under an "extractivist paradigm", Pargman and Wallsten point to the value of exploring how to recombine the accumulation of materials already found in industrialized settings through techniques like urban mining [58]. 3D printing in particular has been highlighted as a developing technology that can be made to support decentralized production in a future of collapse, especially if using repurposed or recycled material [51].

We take up the appreciation of practice, and particularly the destabilizing practices aimed at societal change, as a valuable unit of analysis. Extending Tomlinson and colleagues' position, we consider the tools of innovation, so to speak, from the soldering iron to emerging rapid prototyping systems. Doing so helps expose and address how designers contend with scarcity and extractive relationships at under-studied stages of the design process, not just at the beginning or end. In the sections that follow we explore how these tools might look very different when material limits and scarcity are taken into account in the now: how the traces and trajectories that underpin design work refigure remnants as central materials, a process we term salvage fabrication. In this process, we ask: *How might designers rework fabrication tools in ways that account for and design with the flows of material beyond the maker's studio?*

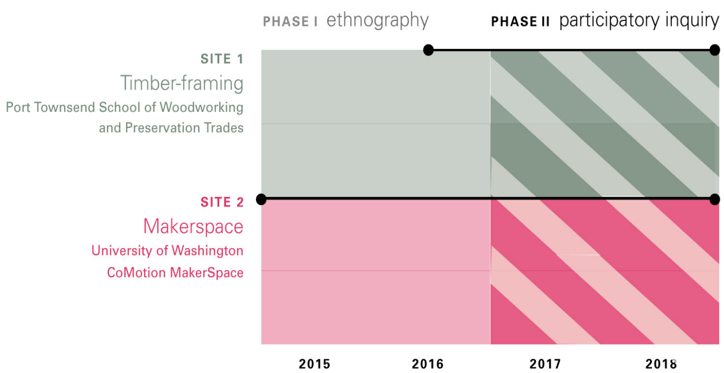

Figure 1: Situating the study

3 APPROACH

To address the above question, we conducted a study of fabrication practice that unfolded across two main phases (see Figure 1 above). In the first phase, we conducted ethnographic work from 2015 through 2018 across two fabrication sites: (1) a timber framing shop in a woodworking school and (2) a university makerspace. In the second phase, Dew followed up this ethnographic fieldwork with participatory inquiry: gathering a design team to explore salvage relationships emerging from the ethnographic sites. Although this paper draws from within and across these three years of data collection, we focus our analysis on the second phase, a participatory design research process that unfolded between 2017 and 2018. Our use of design techniques such as prototyping allowed us to explore the qualities of tooling that draw together salvage concerns from both sites.

3.1 Site 1: Woodworking Shop

The research team began articulating salvage relationships by drawing on two years of ethnographic study at the Port Townsend School of Woodworking and Preservation Trades in Port Townsend, Washington. The school was founded in 2007 to teach woodworking and associated skills. It started out attracting mostly well off older male hobbyists (and still does), but funding and curriculum changes over the past few years have helped draw in younger people, veterans, and women seeking a livelihood in handwork. It has grown to comprise dozens of courses throughout the year ranging from weekend workshops to 3-month intensives and certificate training aimed at people who want to make a living in woodworking. These include courses on traditional joinery and timber framing that Dew completed during fieldwork, revisiting the timber framing course again a year later. In addition to building three timber framed tiny houses with fellow woodworking students, she has collected hundreds of images, plans, and sketches; conducted informal conversations with more than twenty builders around Port Townsend's woodworking community, and recorded ten hours of in-depth interviews with eight key informants chosen for their varying perspectives and depth of experience in woodworking and building practice. Analysis comprised close reading of core texts in the fabrication and sustainability literatures, iteratively annotating the field notes and interviews, ongoing thematic analysis with the research team, and memoing to develop the relationships between core themes. This site attuned the research team to multiple enmeshed acts and scales of a salvage practice and unfolding [re]valuation of the past – in material flows, fabrication method, livelihood, and broader industrial rhythms of decay and resurgence [79].

3.2 Site 2: Academic Makerspace

To contextualize the innovation processes we complement the timber framing fieldwork by drawing from two years of ethnographic study at the University of Washington's CoMotion Makerspace in Seattle Washington, beginning shortly after its opening in 2015. Led by Shorey, this field research at CoMotion has included weekly observation of twenty reoccurring figures—administrators, student leads, and mentors—and informal, active interviews with over fifty makers. Qualitative field data was produced through ethnographic field notes and in-process memos, and was iteratively analyzed throughout the research period [17].

The University of Washington makerspace is embedded in "CoMotion" — a university division previously known as the Center for Commercialization. The Center for Commercialization, and now CoMotion, focus on managing intellectual property for products and discoveries made through research at the university. A central tenant of CoMotion's mission is still "tech transfer," which takes the products of university research and makes them available for further, commercial development in the for-profit sector [6]. Yet, with the 2014 rebranding, the university sought to incorporate a more agile, entrepreneurial spirit that reflects a "truer economic and societal value" [80].

3.3 Participatory Methodology

During the second phase of the project (the focus of this paper), the research team followed two methodologies of participatory inquiry: (1) apprenticeship-led fieldwork [44], a tradition that embraces manual labor, the flux of people and materials, and the lived experiences of developing embodied knowledge that can best be described by doing together; and (2) design inquiry [29][49][71], a tradition that integrates rigorous observation, documentation, reflection, and analysis with collaborative design, building, and engagement around materials, from conductive wire to living douglas fir. Together these approaches prompt researchers to actively attend to how their embodied collective practices undo dominant assumptions around design—in our case, the assumption that design is a process with a beginning and end, with a human in the middle; and that salvage or repair is a making practice that happens only after the production process is over.

In September 2017, the research team brought one of the timber framed houses that Dew helped build during ethnographic fieldwork to an outdoor location near the makerspace. The frame was built on skids so it could be lifted on and off a trailer and moved (see Figure 2 below). We then began meeting weekly with a design team comprising 11 undergraduate and graduate students in design and technology fields to carry out design exercises and hands-on building activities related to the ethnographic themes from the woodworking site. The students applied and were selected for their interests and skills in interaction design, fabrication, design materials, and analysis. Each member kept a sketchbook, sharing their weekly reflections, photos and sketch scans in an online shared folder; each also kept a "process blog" or online workbook (much like [25]) where they document their activities, design process, experiences, and reflection for each week. Meanwhile, Dew moderated and took field notes on the studio activities and discussion; she is thus a part of both the research team and the design team.

Figure 2: The tiny house frame being moved from Port Townsend and set on campus in Seattle

During the first 10 meetings, activities included hands-on building, material biographies, sketching, and field trips exploring wood as a design material. These activities were conducted as a group with weekly critique and analysis in each 2-hour meeting. The five subsequent meetings extended this work by shifting

Figure 3: Foam waste collection at the makerspace

focus to materials specific to the university making context, blending the timber framing sensibilities that take materials scarcity into account throughout fabrication activity with the substances of rapid prototyping: discarded cardboard, foam, wiring, 3D printing filaments, laser cut scraps, sawdust, and electronic components. We tasked each design team member with developing a prototype tool or material out of the waste of technology innovation processes. The goal was not to solve a design problem per se (e.g. waste), but to use design exercises to rethink what acts of 'salvage' and 'fabrication' grounded in the woodworking site might entail in the university's technology production hub.

The research team iteratively analyzed the aforementioned empirical materials, which served as design documentation about the salvage fabrication process [3][17][25][26]. Continually attending to emerging themes surrounding the organization, challenges, and potentials of salvage making followed iterative rounds of annotation and reflexive analysis of the observations from the process blogs by the design team during each 2-hour weekly meeting. They were selected for further examination because they spoke to observations that cut across many of the projects. Following other design research expeditions [59], the reader is invited to consider the projects as both propositions and provocations that move designers through the process of gathering, reconsidering, and reforming the leftovers of technology maker practice.

4 INITIAL OBSERVATIONS: GATHERING FRAGMENTS ACROSS TWO SPACES

Our concern for salvage emerged from our fieldwork at the woodworking school, a site that looks back through history for its tools and techniques. The instructors and students adapt traditional fabrication practices from the past to negotiate the scarcity of old growth timber and the skills to work with it today. The woodshop ordered only one delivery of lumber to build with, young growth douglas fir, because the local old growth that helped give rise to timber framing techniques is no longer easily available. Wood that 100 years ago would have been sourced from a local logger and sawyer now comes shipped in from managed forests in Canada, and the instructors say it is not ideal for timber framing techniques because of its wider grain, moisture content, and other traces of contemporary forestry practices. The area surrounding the woodshop used to be home to a robust lumber industry established by colonialists and later companies to feed the westward expansion in the mid-1800s, but tapered off after railroads arrived farther south and much of the easy-to-access timber had been cut [8]. To ensure enough local old-growth wood for an entire project, even one as small as a tiny house, often required ordering three months ahead if a builder was to get enough from one of the few remaining millers and sawyers in a nearby town. But availability of this kind of timber went in unpredictable rhythms. Wood that grew slowly over many decades was scarce and expensive, so builders used younger fast-growing stock most likely from large managed forests in Canada. Some of the wood was still damp, the grain relatively wide and prone to twisting and warping as it dried, which the builders said was one of the effects of using contemporary forestry and kiln-drying methods prioritizing quick production at the expense of more stable wood. However, even mistaken cuts and warped pieces needed to be saved so they could be turned into smaller components of the building. According to these builders, once a piece was delivered and cut to its mate, a woodworker must "work with what you've got".

These activities at first contrast with the rhythms of the makerspace – where barely a week goes by without a new gadget appearing. High-tech tools arrive wrapped in cardboard, plastic, and foam. Objects emerge from the beds of 3D printers and are stitched around dress forms. Makers transform the once flat materials – fabrics and filaments – into things. Generation occurs in tandem with cutting down, sanding, milling, and winnowing. Leftovers are cast off but then rummaged through by other makers. Students carefully plot out the pieces for their projects in design software, positioning them to utilize every inch of material. Week by week, the waste bins are filled, picked through, and emptied; one week the tip carts are full of cardboard, the next the cardboard is interspersed with sheets of discarded copper printed circuit boards.

In conversations with makerspace members, the capacity for inventions to address social and environmental problems was a common theme. As one young woman put it, she was learning prototyping skills because she wanted to be able to "change what I see needs changing." Making was a hopeful endeavor, impelled by the belief that diagnosable problems can be fixed through attention, skill, and creativity. From this perspective, solutions are in the products of individual innovation, rather than reimagining technological processes.

Bringing the woodworking school's salvage sensibilities into conversation with the materials and tools of the makerspace, the design team explored the leftovers of technology building activities. Taking an attention to scarcity as a starting point, the design team (which includes Dew) searched the makerspace and other campus fabrication labs for scrap materials. They investigated what the material is made of, how it is produced, where it came from, what it's used for, and how it's typically disposed of. They documented their experiences, open questions, and process, and they traced how those materials circulate through sourcing and disposal. Along the way they shared sketches of tools and materials that could help incorporate those scraps into fabrication practice.

During one week's meeting the team shared burnt birch ply and acrylic from laser cutting, scraps of solid core wiring, sensors, metal shavings from mills and lathes, cardboard, steel cabling, moldy wood, chipboard, foam core and EPS foam, scraps of PLA filament and failed prints, cabling, tape, packing peanuts, and sheets of plastic. They passed them around, sharing what they could find out about their provenance and disposal. As they began brainstorming what they could make with the scraps, environmental forces like weather became part of the fabrication process. Collaborator Betsy, a senior undergraduate interested in design research and materials, described a mounting sense of the ambiguities and hazards of scavenging through scraps that had been left out in the Seattle winter rain in her process notes: *"The final thing I grabbed was a small piece of wood from a much larger pile of wood. It was dark outside when I went to find salvaged materials, so I couldn't tell at the time that it was moldy. All of the wood scraps are sitting outside uncovered, so it's possible that many of them will be moldy and unusable. This would require investigation while it's still light outside. It may be possible that the piece of wood (which was broken and had a rusty nail in it) was once part of a pallet."*

The fragments of what might have been a pallet were left out to grow mold and rust in the Seattle rain, rendering traces of exposure to ecological forces central to the making process. When the site of making moved from a well-lit, well stocked and labeled indoor lab to a dark, rainy alley, a sense of risk mounted; the assumption of known, controllable material could no longer be taken for granted when wind, rain, sleet, and fungus mingle in.

The design team agreed during the meeting to take extra precautions. Even materials that seemed innocuous at first, like packing foam, became dangerous when we began thinking through how to reincorporate them for fabrication. We could use food-grade limonene, commonly called orange oil, to dissolve the foam, but swap that for another easily acquired solvent, gasoline, and we'd essentially be making napalm, Betsy learned in the course of her investigations into transforming foam. "Acetone can dissolve foam, but it won't be a controlled dissolve and it's toxic," Gina, another senior undergraduate interaction design student offered. The design team began to speculate: What kind of foam is this? How do we know it's safe to work with? If we make a tool for cutting it, will it release toxic fumes or burst into flames? At the makerspace, cutting foam core in the laser cutter is banned for these same reasons. What about burning or grinding them down – maybe that is even worse for the environment than just throwing them away? What about the chemicals we might need to convert them into workable form? Can we even continue this work indoors? Are we doing more harm than good?

In the context of a sustainability project, material choices take on ethical dimensions. Materials designed to be single use, approved, labeled, and organized in the studio, can become dangerous when trying to wrangle them back out of the wild, revealing both environmental and labor concerns. But the kind of global calculus for benefit and harm is often lost in the local indeterminacies of making. Although making involves plenty of machinery and material, and each can be dangerous when used improperly, approaching tooling for mysterious scraps brings the connections between waste circulations, mystery, and safety to the fore. The questions the design team raised help reveal the differences in risk experienced by those at the edges of production processes – those who scavenge, gather, and sort through the remainders – and highlight how a sense of danger emerged from encountering fabrication materials of uncertain provenance. Having eliminated the most sinister materials and possible tools for working them out of caution, we began reimagining tools for working with the detritus of maker practice.

5 PROBING TOOLS FOR [RE]FABRICATING REMAINDERS

In the nearly three years since its opening, the CoMotion makerspace has become home to a variety of fabrication tools for prototyping. CoMotion currently has a dozen 3D printers, two laser cutters, three othermills, 13 sewing machines, a serger, several AR/VR headsets, a woodshop with power tools, and a lending library of hand tools, along with on-site purchasing for many of the associated materials. In addition, the makerspace contains the typical recycling, compost and waste bins found throughout campus, as well as scrap material collected in two large tilt carts, a transparent bin for foam, a rack of four wire shelves each dedicated to remnants of different leftover laser cutting materials (wood, acrylic, cardboard, mat board), and various cans for the refuse left over from 3D printing, soldering, circuit making, and the wood shop. Tooling in the makerspace often involves materials that exist in abundance right now, from ABS filament to cardboard. Below we draw from our fieldwork in the timber framing studio to consider what tools and tooling processes might look like from the perspective of making within limits; these themes are not discrete or mutually exclusive as they arose during interrelated design processes.

5.1 Ugly Wiring: Highlighting Shades of Time

In the woodshop and later among the design team, sap that bonded over damage, the patterns of growth in the wood's grain, and traces of past trauma in timber knots became glimpses of the wood's life and its encounters with humans, insects, weather and disease. In an early meeting Bonnie, a senior undergraduate experienced in fabrication, located a knot on the timber framed structure that she found interesting because it was protruding and very dark. Looking into why some of the fir's grain is light and some is dark, she found that the variation that produces rings comes from differences in growth depending on the time of year. New wood formed during spring and summer is lighter, and towards the end of the growing season, the growing cells are smaller and have darker, thicker walls. She began sketching a clock that uses differences in grain to show time (see Figure 3). Towards end of growing season, new cells formed are smaller and have darker thicker walls — thus producing a set of contrasting materials for marking information like hours, minutes, or even days.

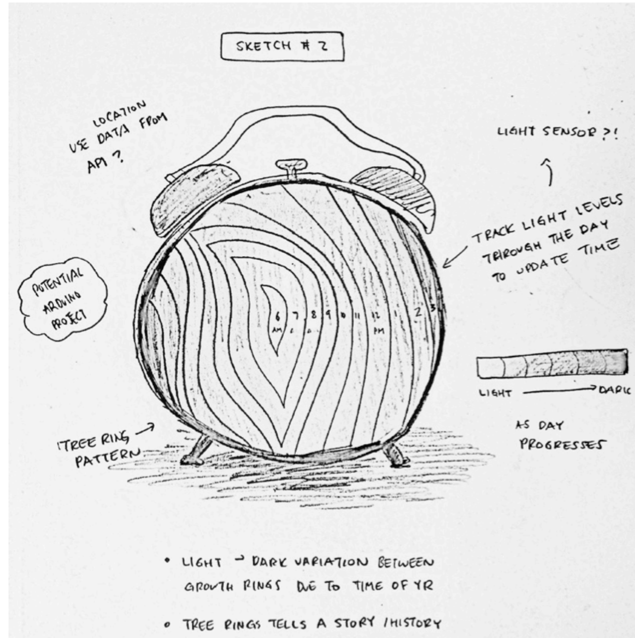

Figure 4: Design sketch incorporating the traces of past growth processes (by Bonnie Tran)

Shifting focus to such traces in making, she documented her idea for a tool to re-spool discarded scraps of wiring: "These materials came from a physical computing project leftover from last quarter…The wiring can definitely be reused for its intended purpose. What would make a wire non-useful, I am not sure. Here, I was thinking about Imperfect Produce [a produce surplus start-up delivering produce boxes in several large US cities], where ugly fruits are packaged and marketed all nice. For a higher

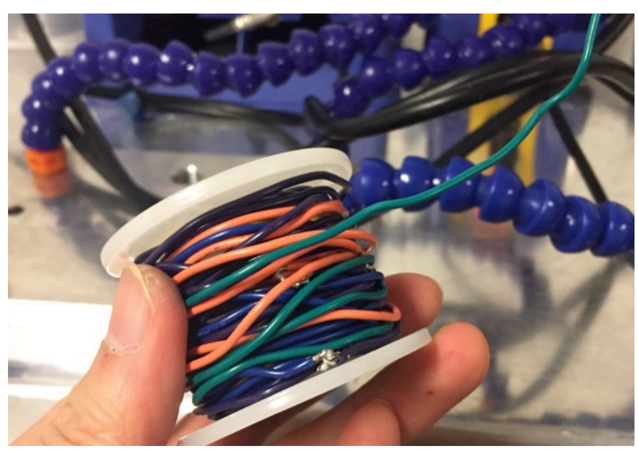

Figure 5: Ugly wiring after re-spooling

fidelity version, it'd be interesting to have a machine where scrap wire is fed into the machine on one end, and comes out re-spooled with the other wires! Imagine an electric pencil sharpener looking box."

Having gathered the scraps and spool needed, Bonnie got to work. She spent a couple of hours re-soldering and re-spooling the wires, describing it as "therapeutic but possibly annoying if there were lots of little pieces". The slowness and care required to re-solder the scraps back together raised a tension with the expectations of rapid creation in technology making. However, it also gave an unexpected relaxing quality to the work when the process of soldering was the ends in itself, not a means to a product or iteration. With her ugly wire soldered and rewrapped, the spool took its place back with the other wiring. Ugly wiring from the spool opened the possibility for valuing 'ugliness', making visible an act of careful repair and re-membering as integral to innovation projects by drawing attention to the traces of past projects and what was considered left over.

5.2 Mitigated Milling: Harnessing Material Inconsistencies

According to our interlocutors in the woodworking school, building a strong structure out of a limited delivery of unpredictable wood meant ensuring the structure would last decades longer than it took the wood to grow. The structure would thus offset the wood we used, giving the material time to regenerate. This process started with a deliberative eye on quality to sort the delivery into different applications, an approach called high-grading. To make the most of the pile of wood delivered, we high-graded by looking closely at the grain and straightness of each piece, reading traces of the fir's past to set aside the best pieces for the walls and the most crooked for cutting into smaller braces. Through this kind of sorting, high-grading helped the woodworker find consistency in inconsistent materials. What might high-grading and a view on long-term mitigation look like in a site of technical production?

Many in the design group found material inconsistencies were not so simple to work with as Bonnie's re-soldering project. Design team collaborator Gero, a senior undergraduate experienced in custom tool building and interested in architectural scale fabrication, found himself drawn to plastics and cardboard, which are abundant. In the process, he quickly ran into questions of how to break those materials down and deal with their inconsistencies: *"how well I am able to manipulate plastics or grind down cardboard and wood… seem to be [challenges that are] prevalent with most projects I can think of... The main reason is that the dimensions and quality of each scrap material will be slightly different, so designing a production process around inconsistent scraps will be near impossible without reshaping the scraps into a more consistent medium. I could work best with finely chipped or ground wood and cardboard scraps, and an easy way to melt and shape plastics."*

But this process required tools for homogenizing unruly materials by sorting and cleaning them, tools that exist in industrial settings but not the makerspace. With Gero's initial explorations in mind, the team conceptualized a mill not for reducing large blocks of material into desired form, as a CNC machine would, but for chopping and sifting the leavings of those production processes. The mill would initially shred cardboard. Once the cardboard became a finer consistency, it could be blended with organic bonding materials (e.g. starch binders) and nutrients to be shaped into restorative forms like composting pots for starting saplings that would clean carbon dioxide from the air. Or the cardboard pulp, pressed into sheets, might grow living materials like moss, which is absorbent, or buckwheat, which can be used to decontaminate soils of heavy metal toxins. Milling invited us to take the remains of prototyping practice and refigure them as materials for environmental restoration via replanting and soil cleaning, extending the resource stewardship sensibilities found in the woodshop.

Figure 6: Milled cardboard

5.3 Perishable Printing: Grappling with Waste

Back at the woodshop, when it came time to cut and fit together pieces of a limited stock of wood, a careful process called "chasing the fit" began. The builder measured, drew and cut one side of the joint, then carried the lines over to its mate to match them as "members" of the structure. Woodworkers needed to work with the members at hand, accepting that even once they're snugly fitted together, the young wood's ongoing warping and broader forces of wear and decay take over. This impermanence of form was celebrated with techniques that draw attention to a joint's changes over time.

Drawing from the woodshop, what would it look like to work with digital fabrication materials precisely because they decay? Design team collaborator Ender, a master's student in design and experienced physical computing hobbyist, started his explorations one afternoon during open work hours at CoMotion: *"I went to one of the guys at the front desk, explained to him the project, and asked him what they were doing with the leftovers from their 3D prints. He became interested right away, and mentioned that this is something that he worries about. He walked me to where the 3D printers are, and showed me a box that sat below them with scrap filament, scrap prints, and some paper. He mentioned that they collect a box of those materials every few weeks, and then throw it away."*

Figure 7: Sketches of salvage fabrication processes

In the course of discussing what we could do with the scraps, which are mostly PLA (a bioplastic manufactured from fermented byproducts of industrial agriculture), one of the students pointed out that PLA is often made of plant fibers and might be able to compost over time. The team began exploring processes for breaking the polymer down (see milling subsection above) and combining it with other compostable makerspace scraps such as wood dust and ground up cardboard. Adapting blueprints found through the recycling project Precious Plastic [28], the team designed an extruder and filaments from the waste that break down more quickly than PLA alone. Instead of using rapid prototyping material for quickly making durable objects, we explored its transient qualities, a material specifically made not to last. In the leftovers of tidy spools of manufactured filament and failed prints, the traces of large-scale agricultural production, manufacturing and the fail fast ethos became a site for highlighting processes of deterioration at work.

6 AGENDA: TOWARDS SALVAGE FABRICATION

With this case, we looked back, through, and around a site of future technology production with a material-driven gaze. We began by noticing what is left behind, categorized as waste: cardboard, foam, and other packaging from the flows of new equipment and materials; and the fragments of technology production. From those traces, we probed tools for engaging resource scarcity, restoration, and marginal methods such as working with decay in order to reimagine some of the core processes of making. At the makerspace, *ugly wiring* reorganized a determinate, instrumental practice into an ongoing piecework process. It carefully bound the remainders of old projects together into an imperfect spool, bringing Bonnie's processes of remembering (and re-membering) into the act of soldering. Through the lens of material inconsistencies, *mitigated milling* became more than a process reducing a block of predictable material into desired form. It allowed Gero to imagine sorting and cleaning the leftovers of such processes to reclaim them as productive again. Across boxes of scraps in the makerspace, *perishable printing* offered a means of inquiring into the leftovers of rapid prototyping. It exposed how Ender's discovery of the remains of fixed objects could be turned into prints that draw attention to processes of decay at work within technology production.

In tracing these potentials, we began to identify a process of salvage fabrication: forms of tooling that take ambiguous, shifting natural resource limits into consideration, accounting for and designing with the flows of material and value within and beyond the maker's studio. In the remainder of this paper, we consider the implications of this process for HCI more broadly. We do not suggest that designers can solve environmental collapse with better tools, but instead consider how tooling provides a means of expanding the purview of salvage practices. It demands looking beyond the empowered individual maker, upcycling enthusiast, or hacker to the wider circulations of material implicated in technology making. Such explorations comprise sites where technology salvage is already happening (e.g. e-waste networks and centers) and where practitioners in resource-constrained environments who are well versed in strategies for making with remnants [33].

In doing so, sustainable design has an opportunity to expand beyond drawing discarded things back into use by an empowered maker-consumer. Complementing parallel consumer mitigation efforts in 3D printing [51], device reuse (e.g. [34]) and what is commonly called the circular economy [22], our efforts begin to open a space for considering and engaging with broader flows of the materials and remnants in fabrication processes, from sawdust left over from young unstable wood to discarded knots of PLA. If the tools of rapid prototyping draw together practices achieved through feats of mass manufacturing with the resource extraction that underpin them, we have shown that it's possible to deploy tools around alternative fabrication values and material qualities that foreground ugliness and inconsistency, scarcity, danger, decay, and restoration. This is not to say qualities like danger are desirable; indeed, this work has demonstrated a need to explore tools and share strategies for working with potentially harmful salvage materials, both as preventative safety measure for practitioners today and as a question of environmental justice – accounting for whose bodies and environments are harmed in the work of technology production. As Pargman and Wallsten [58] and others have pointed out, the unhealthy work of reclaiming materials for use often falls to the less affluent. Complementary interventions with digital technologies could include adapting lifecycle analysis tools to help make the broader health ramifications of technology production more visible, and sharing ways to safely take apart, store and catalog waste that could be reconfigured as valuable again, taking responsibility for waste locally instead of outsourcing unsafe materials and the work of making them useful again.

Next we consider how these insights connect to broader techniques around making: tools for scale-making and tools for re-membering.

6.1 Tools for scale-making

How might designers scale their view of the implications of technology building beyond the reach of the human maker, whose concerns begin in a design moment and end when the discarded prototype hits the waste bin? As our explorations have probed, following materials left to fill waste bins or mold and rust in the rain extends our considerations outward, inviting us to see the slow work of environmental degradation and remediation unfolding in the peripheries and remnants of prototyping practice. Shifting out from studying individuals and problematic consumer practices to tools where design and salvage meet puts making anew and remaking in tension, not by "connecting people *to* their actions and their consequences, but on connecting people *through* their actions and their consequences" [15]. As such, tools for engaging materials and their lives beyond the studio become tools for scale-making, connecting design with the longer temporal frames and broader collectives of ecological forces, people, machinery, and practices bound up in the work of fabrication. Tooling in this way provides a lens for examining questions of environmental justice and political economy in technology production settings.

6.2 Tools for re-membering

Salvage fabrication also charts a different path to making tools for a future of collapse by recognizing that future all around us, actively in progress and open to reworking *now*. This process requires examining the category of remnant. Feminist philosopher Donna Haraway speaks of re-membering as a process of putting back together anew: "To re-member, to com-memorate, is actively to reprise, revive, retake, recuperate" [30]. Cataloging what is left over from a production process is a way of accounting for not only broader environmental impact, as scholars of e-waste have deftly demonstrated [22][45][58], but can also reveal circulations of value in technology production. Remnants show us what matters – what artefacts, materials, tools, and techniques count as central in a fabrication practice [4]. Here, the bins of cardboard and foam from shipping new materials and equipment to the makerspace, discarded PLA prints, and scraps of wiring too short to use alone tell us that the activities unfolding around the waste bins favor fast, globally enmeshed production practices.

Followed over longer periods of time like the young wood used in the timber framing case – or followed outside the studio like the wood from busted shipping pallets left out to mold in the rain – remnants can also provide a glimpse of industrial emergence and decay. Where do remnants pile up? Whose work is it to deal with them? If remnants can highlight what material practices we frame as marginal to fabrication in the here and now – in this case packaging and shipping, fixing and testing, disposing, scavenging, and sorting – we have an opening to change those configurations we find problematic. In rethinking milling and printing, durable detritus could be remade as impermanent and regenerative, reversing material flows from shipping, packaging, and rapid prototyping with PLA implicated in environmental degradation. Fabrication with a salvage sensibility can help reorganize broader patterns of waste and extraction in technology production as restorative.

7 CONCLUSION

This paper has built on research at two ethnographic sites by exploring processes for making that take natural resource limits as a starting point. Alongside tools to change consumer behavior, reduce energy usage and waste, avoid obsolescence, and soften the effects of future collapse, tools with a salvage sensibility show that collapse is already here in the asymmetrical and unpredictable impacts of technology production. To help open the conversation around making within limits, we explored forms of salvage fabrication, an alternative design concept that emphasizes the interconnected material flows into and beyond local processes of material production. The projects that emerged here – ugly wiring, mitigated milling, and perishable printing – open spaces for acknowledging the broader environmental engagements of fabrication through scale-making and re-membering the remnants of technology production. Such tooling invites reflexive examination of who and what is implicated in the greater webs of technology production, reconsidering problem-solution frames that cast sustainability as the work of individual consumers and innovators, and obscuring design's role in scripting broader industrial patterns and trajectories.

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