Nothing Like Compilation: How Professional Digital Fabrication Workflows Go Beyond Extruding, Milling, and Machines

MARE HIRSCH, University of Puget Sound, USA
GABRIELLE BENABDALLAH, University of Washington, USA
JENNIFER JACOBS, University of California, Santa Barbara, USA
NADYA PEEK, University of Washington, USA

Fig. 1. Products made with workflows that included digital fabrication steps. We examined products made with different materials including wood, concrete, glass, fabric, plastic, and porcelain. A: Robotically milled wooden vase by ODK Design, B: 3D printed pendant lamp by CW&T, C: 3D printed concrete table by Fritsch+Durisotti, D: slip cast porcelain cup with plaster mold by Nervous System, E: Jacquard woven textiles by *WOVNS* F: craft beer glasses by Path Design, and G: 3D printed clay cup by Slip Rabbit.

Understanding how professionals use digital fabrication in production workflows is critical for future research in digital fabrication technologies. We interviewed thirteen professionals who use digital fabrication for the low-volume manufacturing of commercial products. From these interviews, we describe the workflows used for nine products created with a variety of materials and manufacturing methods. We show how digital fabrication professionals use software development to support physical production, how they rely on multiple partial representations in development, how they develop manufacturing processes, and how machine control is its own design space. We build from these findings to argue that future digital fabrication systems should

Authors' addresses: Mare Hirsch, University of Puget Sound, Tacoma, WA, USA; Gabrielle Benabdallah, University of Washington, Seattle, WA, USA; Jennifer Jacobs, University of California, Santa Barbara, Santa Barbara, CA, USA; Nadya Peek, University of Washington, Seattle, WA, USA, nadya@uw.edu.

support the exploration of material and machine behavior alongside geometry, that simulation is insufficient for understanding the design space, and that material constraints and resource management are meaningful design dimensions to support. By observing how professionals learn, we suggest ways digital fabrication systems can scaffold the mastery of new fabrication techniques.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**.

Additional Key Words and Phrases: digital fabrication, low-volume production, digital design, CAD/CAM, digital craft, product design

ACM Reference Format:
Mare Hirsch, Gabrielle Benabdallah, Jennifer Jacobs, and Nadya Peek. 2023. Nothing Like Compilation: How Professional Digital Fabrication Workflows Go Beyond Extruding, Milling, and Machines. *ACM Trans. Comput.-Hum. Interact.* 1, 1 (October 2023), 46 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 INTRODUCTION

In 2005, the Swedish collective Front Design exhibited an interactive experience at Design Miami. The artists used a motion-capture system to track and record three-dimensional sketches of chairs, tables, and lamps they drew in mid-air [18]. The accompanying video showed the all-woman collective sketching furniture shapes in space, with extruded lines following their pen strokes superimposed as augmented reality [19]. The resulting gestures were recorded and 3D printed as life-sized functional furniture using a 3D printer normally used for racing car parts [72, p. 770–771]. Front Design's Sketch Chairs are notable because they present a vision for the future where digital fabrication transforms the design and production of physical products—a vision that persists to this day [27]. The Sketch Chair workflow exemplifies many of the opportunities the human-computer interaction (HCI) research community now considers core to digital fabrication, including mass customization [75], precise and efficient robotic manufacturing [70], the reduced time between design and production [77], new computer-aided design interactions [99], and new aesthetic and functional possibilities for consumer products [66]. Front Design's performance also showed how digital fabrication might alter the status quo of who participates in design and manufacturing. By presenting a furniture design workflow centered on drawing, they suggested that anyone who could sketch could also design and manufacture a piece of furniture.

The Front Design exhibition occurred at a time when digital fabrication was gaining increased attention as a potential consumer technology. The same year marked the start of the RepRap project—an open-source initiative to create a low-cost, widely available 3D printer [44], the launch of Make [101]—a magazine aimed at do-it-yourself (DIY) enthusiasts, and Gershenfeld publishing FAB—a vision of widespread digital fabrication revolution that equated digital fabrication design tools and machines with personal computing [33]. Digital fabrication has continued to grow in access and application in the decades since. Digital fabrication machines such as 3D printers have decreased in cost, making it feasible for a broader group of practitioners to access them [28, 34]. This increased access and potential for broader engagement have fueled a rise in community makerspaces [11, 61], the development of consumer and hobbyist-oriented digital fabrication equipment [62, 89], and the creation of application-specific [85] and entry-level design software [83]. The overarching goal of democratizing design and production is embodied by the Maker Movement: a collection of social and commercial efforts that have grown alongside the proliferation of digital fabrication technologies.

The growth in digital fabrication access has significantly shaped HCI research. Motivated by the ethos of the Maker Movement and the opportunities of widespread and diverse fabrication technologies, HCI researchers have focused on developing easy-to-use digital fabrication design tools and fabrication techniques by simplifying digital design processes [39, 52], enabling creators to reuse and remix existing 3D models [75, 86, 96], creating bridges between digital and physical representations [7, 57, 84], and automating the fabrication of complex assemblies such as mechanisms and joints [53, 56]. Yet, despite the proliferation of digital fabrication equipment and extensive systems research aimed at novice-oriented digital fabrication tools, the actual impact of digital fabrication on design and production is unclear. Proponents of the Maker Movement have argued that increased access to digital technologies could fundamentally transform and revolutionize manufacturing practices [4, 33] and blur the boundaries between professional manufacturers and hobbyists. Despite the growth in access, however, the degree to which digital fabrication tools actually empower new creators remains an unresolved question [1, 60, 69, 100]. It is also unclear how the characterizations of "makers" in HCI digital fabrication systems research align with the actual practices of people who are engaging in independent or decentralized forms of production. Critics of "making" have pointed out how promotional aspects of the Maker Movement frequently reinforce existing power dynamics and demographics in engineering while ignoring the technological contributions of communities who have historically been disenfranchised or unrecognized as technological innovators [2, 15]. There is also evidence that digital fabrication has been adopted by people who do not identify as "makers" per se, but as professional artists, industrial designers, or traditional manufacturers [16, 59]. These practitioners can arrive at digital fabrication with extensive existing expertise in making physical objects, yet be hampered by the assumptions that are built into tools and systems [17, 64]. Furthermore, HCI systems research frequently aims to support "novice" makers and categorizes making expertise along the axis of computational proficiency [8]. This framing ignores other forms of expertise that contribute to innovative or robust outcomes in digital fabrication [22].

We are enthusiastic about the potential of new digital fabrication tools and techniques to broaden engagement in making and see opportunities to better understand the relationship between the visions that motivate the design of novel digital fabrication technologies and contemporary digital fabrication practitioners. In particular, we see opportunities to productively inform the design of future digital fabrication systems by examining the practices of individuals who are currently using digital fabrication to design and manufacture commercial products. Our guiding research questions are:

(1) What are the workflows of people who use digital fabrication to manufacture products in low volume? How do they leverage expertise and approach learning new skills in their development and production cycles?
(2) How do existing digital fabrication technologies and their associated software support the design, manufacture, and sale of customized products?

To explore these questions, we examined digital fabrication product workflows by conducting interviews with 13 professional designers, manufacturers, and craftspeople. We limited our inquiry to people who used digital fabrication to create products intended for sale in production runs of fewer than 10,000 items. We focus on low-volume production because it requires creators to negotiate tasks unique to digital fabrication, including designing custom items, regularly (re)programming robots and machines, and providing interfaces for consumer-customized design. These tasks exemplify the perceived opportunities of digital fabrication promoted by HCI researchers and Maker movement advocates alike. We explicitly do not focus on people who are using digital fabrication predominately for recreational or educational goals or people involved in only one step of a production cycle such as contract manufacturers [40, 103]. This is because, in preliminary observations, we noted that practitioners producing in low-volume were developing their own tools and techniques to address barriers, unlike practitioners who instead shaped their business around a set of tools or existing workflows (e.g., a water jet cutting job shop). We also excluded manufacturers who use digital fabrication for high-volume production, e.g., Apple CNC milling phone enclosures or Adidas 3D printing shoes because high-volume producers can invest up-front capital in workflow development that is more in line with traditional manufacturing. We primarily selected interview participants who sold their products because we observed that goods intended for sale were more consistently subject to high demands on quality and consistency, as well as subject to common constraints of timelines and costs.

Through interviews with people producing in low volume using digital fabrication, we sought to capture a detailed description of the workflows participants used for their products and services research, development, design, manufacturing, distribution, and marketing. By focusing on the practices of skilled designers and manufacturers who make products in low volume, we aimed to reveal the ways in which current digital fabrication systems and tools constrain design and manufacturing processes. Doing so enabled us to observe when and where creative decisions are made in these processes, what limitations professionals encounter, and what strategies they develop and sometimes share to consistently achieve high-quality products. Our focus on low-volume production differs from prior studies of real-world digital fabrication use. Previous studies of professional fabrication workflows largely focus on a single firm [16], individual community [25], or practices with a specific machine [5]. In contrast, we compare the workflows of products created with different materials (textiles, glass, metal, wood, concrete, porcelain, and plastic), machines (robot arms, 3D printers, CNC milling machines, Jacquard looms), and fabrication methods (extrusion-based additive fabrication, molding and casting, subtractive fabrication, and end-user customization). As a result, our research reveals shared practices and barriers across different forms of digital fabrication production. These insights suggest opportunities to develop new digital fabrication tools that will generalize for different manufacturers and products in practice. Other researchers have previously explored different digital fabrication environments [6] and the attitudes of digital fabrication professionals [103]. Our work is distinct in our focus on product development. Our participants' livelihoods depend, in part, on selling products, as opposed to maintaining operating machines, conducting research, or serving as an educator. As a result, we provide concrete examples of how digital fabrication has been used for manufacturing commercially viable products as opposed to prototypes or personal projects.

Our contributions are as follows: (1) We describe the workflows of nine products made using digital fabrication in detail, highlighting four categories as a starting point for comparison: extrusion-based digital fabrication, molding and casting, subtractive fabrication, and end-user product customization. The products span materials including wood, glass, textile, porcelain, and concrete. (2) Drawing from these workflow descriptions, we conceptualize four cross-cutting themes: how software development supports physical production; how digital fabrication professionals rely on multiple, partial, and ambiguous representations; how people develop robust product-specific manufacturing workflows; and how machine toolpaths form their own design space. (3) Through a discussion of the products and cross-cutting themes, we surface recommendations and opportunities for HCI digital fabrication research to address challenges in low-volume manufacturing. Specifically, we argue that parametric design technologies should support the exploration of machine settings and material behavior in addition to exploring variations in geometry; that computational simulation is not sufficient for envisioning the product design space; that digital fabrication professionals need to constantly learn as workflows rely on multiple types of expertise; and that material constraints and resource management are design dimensions to support, not realities to flatten or optimize. Our recommendations provide insight for future systems research to support professional digital fabrication practice. Furthermore, our findings suggest pathways for supporting new entrants to low-volume product design and manufacturing by demonstrating the ways professionals develop expertise through fabrication practice which, in turn, informs product design. By observing how professionals develop expertise, we suggest ways digital fabrication systems can scaffold the mastery of new fabrication techniques.

2 RELATED WORK

HCI and computer-supported cooperative work (CSCW) research has a rich history of studying collaborative work across levels of expertise. For example, Gantt and Nardi [32] studied how people with varying backgrounds used, customized, and extended Computer-Aided Design (CAD) software to design physical products. In studying the practices of professionals, they found that people who extended CAD tools were mainly domain experts in design and manufacturing, rather than expert software developers. That way, the teams avoided "the need to expend great effort translating [fabrication] domain knowledge to computer experts." We build upon these prior insights that expertise is not a single dimension that ranges from novice to expert but is made up of many types of expertise.

Specifically, using digital fabrication in low-volume production partially relies on computational expertise, but also relies on traditional manufacturing skills and techniques. Therefore, we draw from prior work that examines the relationships between computation and craft: both how digital design and fabrication influence craft and design practice, and how digital design and digital fabrication technologies are shaped by the people using them. In this section, we provide an overview of related work and what we believe our research contributes to these areas.

2.1 Current Computational Fabrication Practices

Tools and materials are key to craft practice. Prior HCI research has shown that the material expertise of craftspeople such as textile artists or woodworkers informs their explorations of new technology and motivates them to modify and extend tools to suit their practice. Cheatle and Jackson [16] provide a rich account of how high-end furniture makers develop new forms of craft, care, and creativity when adopting robotic fabrication processes. Other studies on craftspeople and computer control corroborate these findings and situate making practices beyond humans in a larger ecology of living materials [25, 43, 74]. Devendorf et al. [22] give suggestions for how HCI/engineering can engage with people with craft expertise, recounting that after their productive weaving residency they "came to see that our assumptions about what counted as "technical" were more narrow than they ought to have been." Like this prior work, we argue that these accounts of current practices of domain experts have design implications for future digital fabrication systems.

HCI researchers themselves have also directly engaged in making practices [35, 38, 78, 107]. For example, by producing digitally designed ceramic artifacts, Wakkary et al. [98] and Rosner et al. [82] show how nontrivial design challenges emerge when moving from software to physical materials, and how material expertise can inform decisions in CAD. By engaging in making practices directly, HCI researchers can explore nuanced details and gain deep insights into the process. However, the products we study here include large-format and costly items made in low-volume. These would be non-trivial to develop in academic research labs. Therefore, studying these products gives insight into challenges that persist across a range of scales, materials, and machines.

We also draw from prior research into digital design and fabrication processes. Other research has focused on sites of practice. In particular, makerspaces are now widely-available sites providing access to digital fabrication technologies. By studying makerspaces and maker culture, HCI researchers have investigated who is using makerspaces [21, 55, 65, 69], how they are making [26, 81], what tools they might want in makerspaces of the future [6, 103], and whether these spaces are fulfilling the Maker Movement vision [1, 60]. Rather than center on makerspaces, we focus on specific products intended for sale and the workflows people developed to realize them. The products we study relied on a combination of in-house facilities and conventional manufacturing sites. Our work is also distinguished from prior research focusing on product creation by creators who use a single digital fabrication technology to manufacture products [5]. Instead, we present a comparison and categorization of creators working across a wide range of different digital fabrication machines, materials, and design methods. As a result, our findings highlight how pursuing different opportunities in digital fabrication impact the kinds of labor practitioners undertake, while also revealing shared practices and barriers.

We believe that how craftspeople are currently approaching digital fabrication should inform future tools. Through our research, we provide further insight into current digital fabrication practice and discuss how this could inform future systems research.

2.2 Workflows and the Legacy of CAD/CAM/CNC

Digital design is a prerequisite for digital fabrication. However, digital design also can create unproductive boundaries in the design workflow. Prior work has shown how designers can use CAD to retain power over other stakeholders in a project [80]. The introduction of Computer-Numerical Control (CNC) and Computer-Aided Manufacturing (CAM) as a way to automate industrial manufacturing equipment was fraught with power negotiations between labor and management: there was a stark contrast between managerial beliefs that CNC machines could be "run by monkeys" [73, p. 270] and the actual machinist skill required for programming and operating CNC mills [73, ch. 11]. Artifacts of these historical boundaries persist to this day and manifest in software.

Recent research has shown how adhering to rigid steps delineating design and fabrication and increasing automation hinders people from developing novel workflows. For example, Li et al. [59] show how digital artists benefit from being able to move between digital and physical manifestations of a design but encounter barriers when working across black-boxed software representations or high-level automated design functionality. Gulay and Lucero [36] review the divide between digital and physical design in professional architecture settings and argue for the development of "fluid-feedback based" workflows that prioritize materialization and physical input. In particular, prior research has shown that friction arises between CAD and CAM steps in digital fabrication. For instance, designers are hindered by boundary representations in CAD when designing for volumetric fabrication processes like 3D printing [64]. Studying the practice of a plotter art community, Twigg-Smith et al. [97] explicitly argue that in digital fabrication workflows, "opportunities for creative exploration are more important than seamless control." Friction in digital fabrication workflow exploration is an active site of inquiry [31, 94, 105]. The people we studied in this paper further highlight how the combination of digital design and digital fabrication is far from seamless. By comparing and contrasting their workflows, which span different materials and scales, we provide insight into common issues and problem-solving strategies. This allows us to conceptualize workflows beyond a simple CAD/CAM/CNC model and better articulate the needs of groups engaging with digital fabrication through novel workflows.

2.3 Fabrication Systems Research in HCI

HCI researchers have developed systems aimed at reducing the challenges of digital fabrication through automatically generated parameter spaces for fabricating specific artifacts or mechanisms. For example, Yao et al. [102] created a technique to automatically produce furniture joinery, Lau et al. [54] developed a technique to subdivide existing furniture models into "fabricatable" pieces, and Leen et al. [58] built a tool for automatically generating joints for laser cutting. Researchers have also developed design tools that constrain modeling operations to ensure users design artifacts that can be fabricated. Baudisch et al. [9] created a system that restricts people to designing volumes made of laser-cut boxes, Shugrina et al. [91] automatically converts existing geometry to parametric models and Schulz et al. [88] automate alignment and placement of geometry that designers select from a database of existing parts.

While varying in application domain, these examples share the motivation of supporting "novice", "casual", and "non-expert" designers by removing the "tedious" or "challenging" task of ensuring fabrication validity. This motivation is summarized in [8]'s survey of personal fabrication systems wherein they argue for developing hardware and software that embodies fabrication expertise and enables consumers to circumvent professional product designers and manufacturers.

Supporting non-experts through automated parameters and constraints presents a tradeoff: as the degree of design automation increases, so does the level of abstraction. A high level of abstraction can reduce initial difficulties, but it also eliminates the design opportunities that come from direct experimentation with materials and fabrication processes. Varying hardware and machine settings can result in new design spaces and fabrication techniques. HCI researchers have directly demonstrated the design opportunities of modifying digital fabrication machine behavior by developing new form-factors and material properties through experimentation with machine settings for existing digital fabrication technologies [3, 30, 63, 95]. It is also possible to design digital fabrication systems that are oriented towards fabrication exploration, by exposing machine behavior parameters to the designer [23, 24, 31, 94].

Our work contributes to future fabrication systems research by highlighting the role of parameter exploration in developing innovative digitally fabricated products. Our participants developed their workflows through the exploration of low-level fabrication parameters across digital design and machine control. This practice enabled them to develop expertise and conceive of novel design spaces. By detailing the specific workflows across different fabrication machines, materials, and products, our research suggests there are limitations when developing hardware and software that embodies fabrication expertise. Moreover, our work challenges the vision of personal fabrication as a method to enable *immediate* physical output based on complete digital representations [8]. We show how engaging in the digital fabrication *process* is critical to determining the fabrication output.

3 METHODS

Our research objective is to better understand the practices of designers and manufacturers who use digital fabrication for low-volume production. To do so, we conducted a qualitative analysis of the workflows surrounding nine different artifacts. We compared and contrasted artifacts according to their material and manufacturing processes. This comparative approach enabled us to surface common tensions and trade-offs across all nine workflows despite the variety of other factors that shaped them.

3.1 Research Team

The research team is comprised of professors and graduate students at public universities who collaborate in research on digital fabrication. In addition to studying the practice of digital fabrication, the research team also engages in practice-oriented digital fabrication research. As a result, the authors had direct experience with many of the software technologies and CNC machines that were used by the participants. Our use of these technologies in the context of academic research is different from their application in product design and manufacture; however, our practical experience directly informed our interview methodology and workflow analysis.

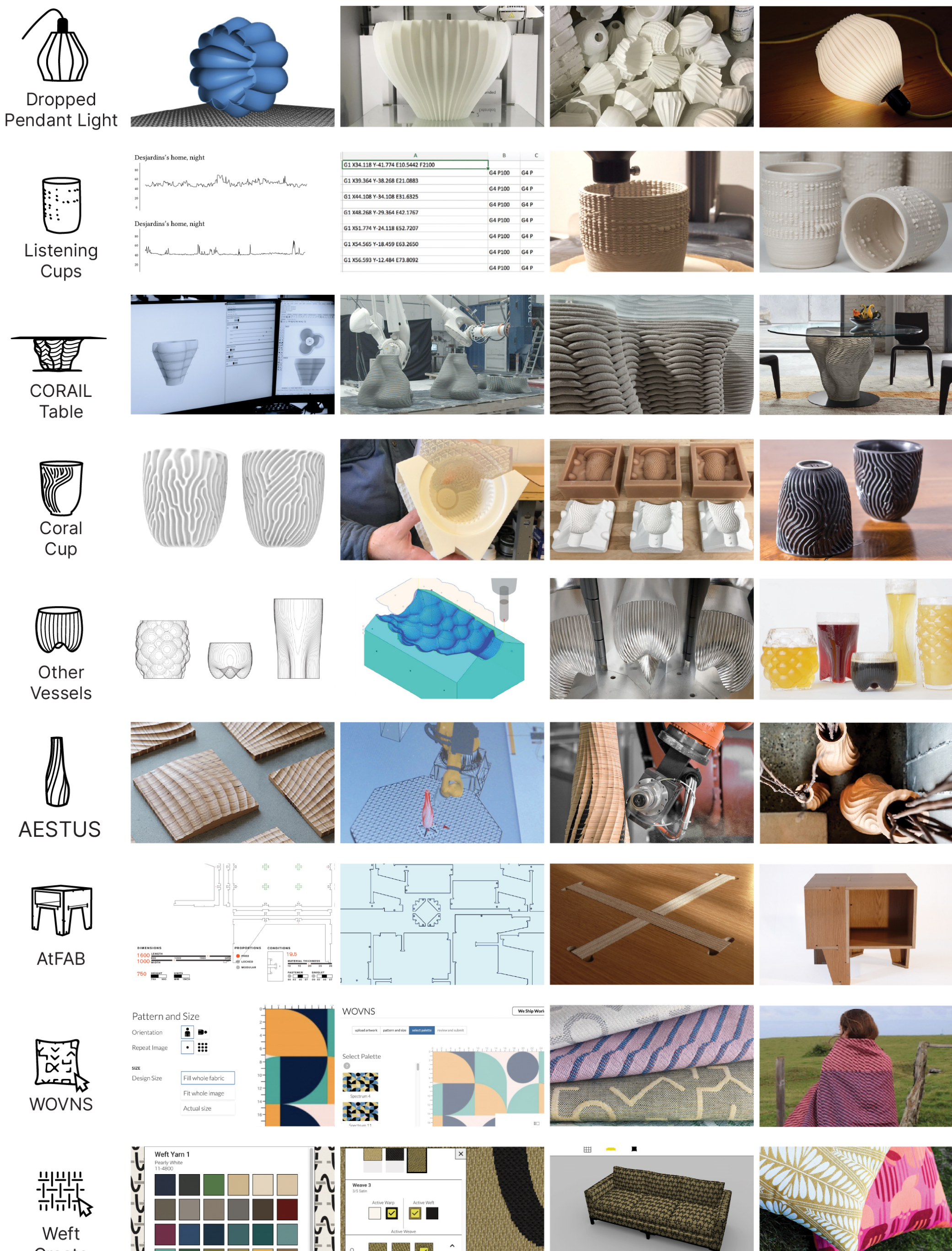


Fig. 2. An overview of the nine products we considered. For each product, we show a variety of digital models, toolpath simulations, intermediate objects such as molds, end-user customization interfaces, and the final products.

3.2 Products and participants selection

We selected artifacts according to the following criteria:

(1) Tools: The products were made with digital fabrication tools.
(2) Scope: Products were manufactured at a low-volume production scale.
(3) Design Quality: Products showed evidence of commercial or critical success.

We started with a preliminary selection of artifacts that fit those criteria. We then narrowed down the selection by choosing pairs of products that either used a similar manufacturing process but had different form factors or were made out of the same material but not with the same tools. We selected each product based on the documentation available on the participants' websites, media coverage about the products, and, in four cases, the authors' first-hand knowledge of production from site visits. We conducted these visits as a part of our broader digital fabrication research agenda. They provided a means for the research team to develop a relationship with participants and have physical experience with their products and working environments.

Our selection focused on *products* rather than organizations or individuals; this decision is reflected in our findings, where the emphasis is placed on descriptions and analysis of production workflows rather than individuals' experiences. These pairings highlight the fact that products that look similar can exist on different design and manufacturing axes, such as material and fabrication techniques. Given the wide range of factors that shape digital fabrication workflows, such as design intent, commercial objectives, skill, scale, aesthetic motivations, and access to resources; pairing artifacts according to manufacturing techniques and material similarities enabled us to better understand how these other factors shaped the workflows. We show each of the nine products we selected, namely *Dropped Pendant Light, ListeningCups, CORAIL Table, Coral Cup, Other Vessels, AESTUS, AtFAB, WOVNS*, and *Weft*, alongside images of different stages of their workflows in Figure 2. These nine artifacts are grouped into four fabrication methods: additive manufacturing, subtractive manufacturing, molding and casting, and end-user customization, and seven materials: plastic, porcelain, concrete, metal, glass, wood, and textiles. In Figure 4 we highlight the materials and fabrication processes for each product.

Throughout this paper, we refer to our participants and their companies by their real names. We received explicit permission in our interview consent process to do so, as well as permission to include images of the interviewee's processes and products. Our approach acknowledges prior advocacy in HCI to attribute creative accomplishments to their creators [14, 16, 97].

3.3 Interviews

The names and companies of the thirteen people we interviewed are listed in Figure 3. Our interviews reflect the collaborative nature of digital fabrication-enabled design and manufacturing. Several participants are members of the same company and worked together to develop a product. This was the case for Jessica and Jesse from Nervous System and Che-Wei and Taylor from CW&T. In other cases, we interviewed participants at separate companies who collaborated on the same product. For example, XtreeE and Fritsch+Durisotti worked together to develop the CORAIL dining table. Interviewing people who collaborate in teams across different domains of expertise and with different tools was conducive to our research aims, as it made explicit the development of processes that were legible across team members with varying types of expertise. In Appendix Table 1 and 2 we provide additional information for each participant, including the participants' background, education, available resources, collaborators, and the software, materials, and equipment used to produce each product.

We conducted eleven semi-structured remote interviews with our participants over the course of four months. For four products, our interviews were informed by prior visits to the participants'

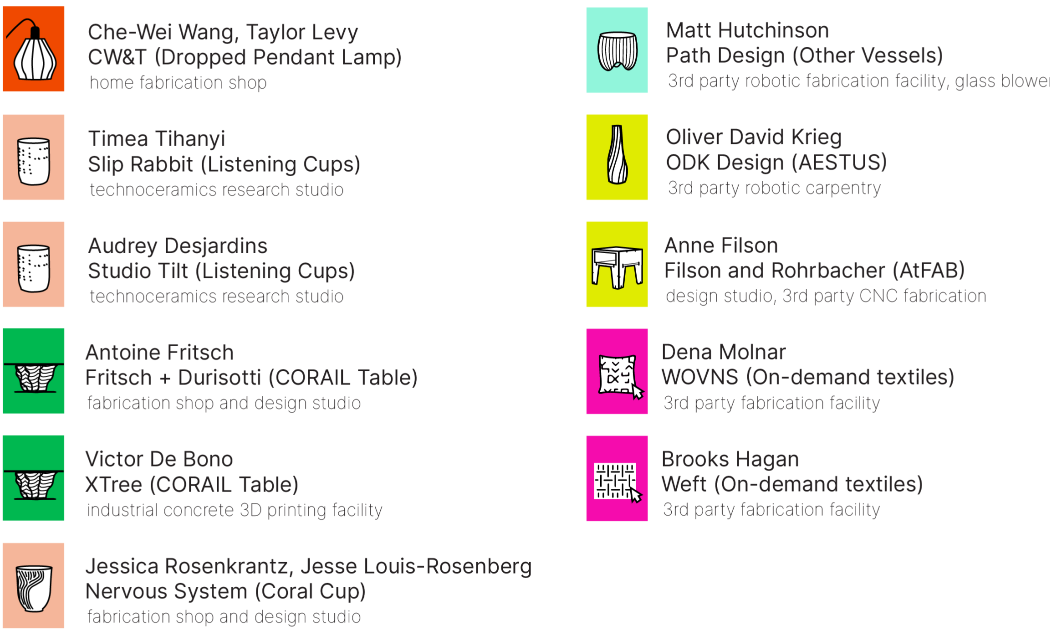


Fig. 3. The participants we interviewed along with their products and facilities. The colors for each product background correspond to the materials plastic, porcelain, concrete, glass, wood, and textile, and are labeled in Figure 4. These icons are used as visual references to the products in this paper.

workspaces and studios. We visited the personal studios of CW&T, Nervous System, and WOVNS, which are co-located with their residences. We also visited and worked in the industrial fabrication workshop used by Path Design. These site visits familiarized us with the range of fabrication technologies used in the production of many of the artifacts from our study. Furthermore, for all of the artifacts except for *Other Vessels* and *AESTUS*, at least one author physically handled the artifacts.

Interviews lasted approximately one and a half hours. Participants spoke about their professional backgrounds and the genesis of their company or studio and proceeded to describe their workflow according to five main categories: prototyping and design; software development (if applicable); production (if applicable); distribution, marketing, and pricing; and documentation. We developed a tailored interview framework for each product that reflected these categories with product-specific questions. We integrated our prior research of each product and our practical experience with the software and machines used in each product's creation to target questions about the technical decisions made at each step of the design process. For example, we sought to gain details on the specific settings and modes used in a slicing software tool, the nozzle diameter for a clay 3D printer, or the particular endmills used to achieve a specific milling effect. We refined our interview framework after each interview. Participants often shared their screens during the interviews to make visible aspects of their workflows such as their in-house software or documentation. In some cases, the participants gave virtual tours of their studios or workshops.

All interviews were audio recorded and transcribed. After each interview, we discussed initial observations and impressions. This process allowed us to fine-tune our questions and start forming a broader understanding of the challenges and trade-offs our participants encountered.

3.4 Data Analysis

We used two strategies in our data analysis: reflexive thematic analysis and workflow descriptions. Once all the interviews were completed, each author individually open-coded a set of two or three interviews. We then met to discuss the initial round of coding. Two main types of codes emerged through this process: *descriptive* and *interpretive*. Descriptive codes referred directly to steps in the workflows. These codes led to the emergence of nine workflow categories, which we describe in detail below. Interpretive codes (for instance: *collaboration with engineering experts; labor reuse;* or *tacit representation*) surfaced approaches, strategies, tensions, and attitudes towards the workflow itself. The interviews were cross-coded and through several rounds of discussions, we calibrated our codes. These discussions also revealed early patterns and key points which we conceptualized into four main themes, described in Section 5 of this paper.

After completing thematic analysis, we wrote a description for each artifact's workflow. The workflow descriptions provide concise and high-level summaries of each interview. As such, they offer rich vignettes of digital fabrication workflows and help to understand the diversity of approaches, challenges, and contexts of our participants. From the workflow descriptions, we outline key steps of the fabrication processes. Despite the differences in each workflow, we sought to identify categories of workflow steps that were common across the nine products so that we could more constructively compare and contrast across workflows. The nine digital fabrication workflow categories we developed from our descriptive analysis are:

(1) **Concept development:** Activities that lead to the concept.
(2) **Software development:** Designing and engineering a novel software tool.
(3) **CAD work:** Modeling geometry in commercially-available software.
(4) **CAM work:** Specifying CNC machine and robot behavior.
(5) **Physical prototyping:** Creating physical representations that inform product design.
(6) **Process prototyping:** Testing one or more fabrication steps to ensure production viability.
(7) **Production:** Any step required to manufacture a finished product.
(8) **Marketing:** Communicating company brand or product value to customers.
(9) **Distribution:** Selling and delivering physical goods to customers.

These categories are not used in the workflow descriptions. Rather, we used these categories as a way to create common ground across the nine products we studied, which helped with surfacing the cross-cutting themes we describe in Section 5.

3.5 Limitations

Due to the COVID-19 pandemic, we relied mainly on video conference interviews. Verbal descriptions of the workflows were supplemented with screen-sharing and collection of supplementary data from the participants when available, which mitigated our lack of access to fabrication spaces and manufacturing facilities during the interviews themselves.

Previous relationships between some participants (Nervous System, CW&T, and *WOVNS*) and the authors lead to increased knowledge of these products and of their related fabrication workflow. We acknowledge the possibility of social desirability bias, yet found that the personal connections with the participants made them comfortable and contributed to detailed responses.

We selected products that were manufactured in low volume using digital fabrication tools and that were either commercialized or intended for sale. While the *ListeningCups* were not sold, we included them in our selection because Timea develops 3D-printed ceramics with a high level of finish and functionality that show evidence of commercial or critical success. She is represented by Linda Hodges Gallery and sells Slip Rabbit pieces through her own website. In the case of the

ListeningCups, the success was critical, as indicated by its inclusion in the proceedings of the ACM conference on Designing Interactive Systems in 2019 [20].

We focused on participants' qualitative descriptions of software development, parametric representation, and machine settings. We did not directly review software source code, parametric models, or toolpath files. In many cases, this information was proprietary, and review of such data was not permitted by our IRB. Future research examining more granular software engineering decisions through code review or direct observation of software engineering would likely yield additional insights into software development for digital fabrication practitioners, however prior research in other domains of software development with this degree of granularity often relies on administering controlled software tasks [13, 50]. This form of data collection was beyond the scope of our breadth-oriented study of entire product workflows.

Finally, our participants were all highly educated and affiliated with well-resourced institutions. We engaged with this specific set of practitioners because their backgrounds and their professional experience enabled them to develop workflows that demonstrate a high level of design skill, manufacturing knowledge, efficiency, and inventiveness. The products they developed, consequently, derive from a different manufacturing model and ethos than that of mass manufacturing, which rationalizes design and production processes to lower cost and increase volume. In the process, the costs of production are often offset by the environment and labor force [92]. The participants' emphasis on distinctive aesthetic exploration and the original process development that comes with it is reflected in the cost of the items—as well as their need to make a living.

Our participants' access to materials, facilities, and digital fabrication equipment reflect the professional labor they engaged in to secure the means to produce their products. We recognize that our participants rely on equipment and materials that are not widely available in the broader maker community. The question of access in digital fabrication practices is an important one, and it is beyond the scope of this paper. We believe the lessons of these cutting-edge and necessarily well-resourced fabrication processes yield insights for future digital fabrication systems that can support a more broad and diverse population in gaining similar expertise and fluency in design and manufacturing.

4 DIGITAL FABRICATION WORKFLOWS

This section describes workflows for each of the nine products we studied, *Dropped Pendant Lamp, ListeningCups, CORAIL Table, Coral Cup, Other Vessels, AESTUS, AtFAB, WOVNS*, and *Weft*. Photographs of the products and their processes are shown in Figure 2. These product workflows vary in the materials, machines, and fabrication processes used, and some workflows combine multiple materials, machines, and processes. In Figure 4, we categorize the materials and fabrication methods used in each of the products and highlight products that belong to multiple categories. The following workflow descriptions are presented according to the primary fabrication process used in each: *Extrusion-based Additive Fabrication, Molding and Casting, Subtractive Fabrication Workflows, and End-User Customization of Products.* Due to the high number of product workflows presented in this section, we provide background details on each product in tandem with the workflow descriptions to help familiarize the reader with the nine products.

4.1 Extrusion-based Additive Fabrication

Extrusion-based additive fabrication is the targeted deposition and fusing of material, usually layer upon layer [51]. CAD models are used with CAM software to create toolpaths, i.e., instruction codes for CNC machines such as 3D printers. When using additive fabrication processes, makers must account for material aspects such as thermal properties and curing times, as well as machine aspects such as nozzle diameter or feed and speed rates. Furthermore, makers must make model-appropriate

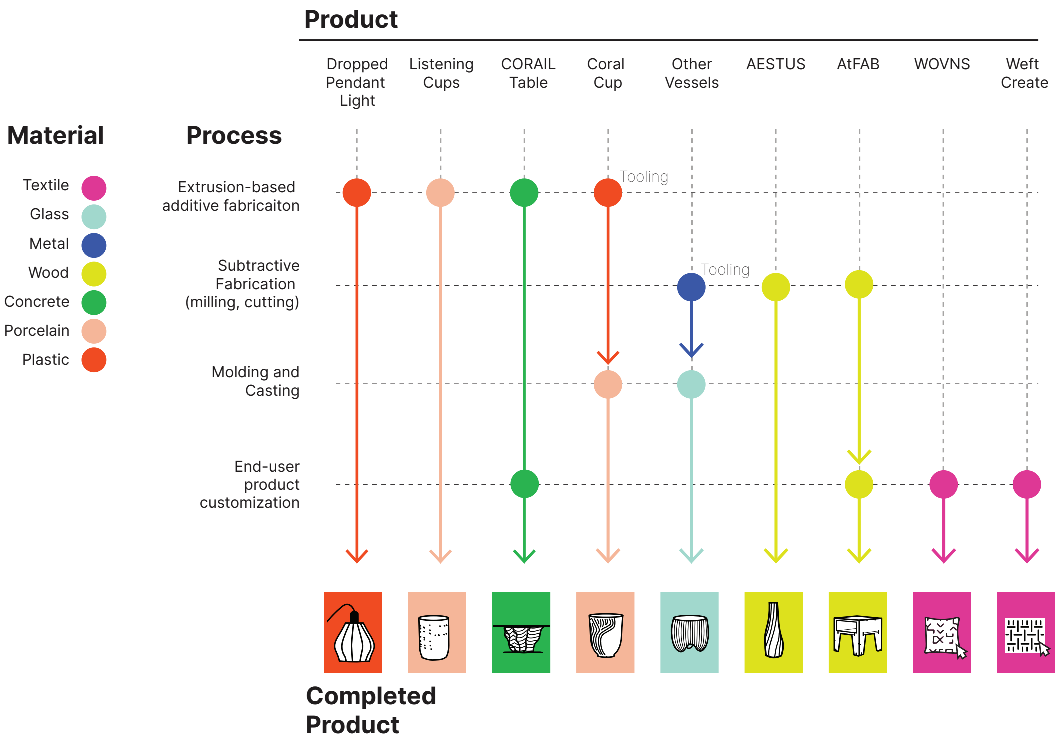


Fig. 4. The products we studied and the primary processes used in each: Extrusion-based Additive Fabrication, Molding and Casting, Subtractive Fabrication Workflows, and End-User Customization of Products. *Coral Cup* and *Other Vessels* used distinct processes for tooling and their final products, namely 3D printing of plastic tooling to produce molds for porcelain casting and CNC milling aluminum molds for glass blow-molding. We will use product icons and color codes for each material (left) in this section.

choices for printing such as print density and support structures. These choices are interdependent in how they impact the final product. For example, higher infill leads to stronger objects at the expense of print duration and material use. Support structures can reduce runtime failures but at the expense of surface artifacts where support is removed from the model.

We studied three products in which extrusion-based additive fabrication featured prominently. All three workflows for these products used specific approaches for generating toolpaths in support of specific production goals. In particular, all three products required continuous material deposition throughout the toolpath. For these products, uninterrupted material flow provided more desirable surface texture and faster fabrication times. This meant that any machine jogging, i.e., any motion of the machine without extrusion, needed to be minimized or fully eliminated. To achieve this, our participants created custom software for generating their toolpaths. They declined to use off-the-shelf software, as novice-oriented 3D printing slicing software automates many aspects of CAM and toolpathing, constraining their options for customization and parameterization [9, 90]. Rather than a straightforward translation of geometry, our participants described complex and iterative CAM work as a large part of their workflow development efforts—during which they furthermore relied on prior knowledge of materials, machines, and software customization.

4.1.1 Dropped Pendant Light. CW&T is a design studio based in Brooklyn, NY run by Che-Wei Wang and Taylor Levy. They design and manufacture goods such as pens, containers, and lamps, which they market and distribute through the crowdfunding site Kickstarter. Their idea for the *Dropped Pendant Light* stemmed from a Kickstarter initiative focusing on runs of 100 products [48]. CW&T sought to make 100 *unique* lamps using 3D printing and parametric design. In their workflow, CW&T iterated through stages of design, process prototyping, and production. They designed parametric models for lamp geometry in Fusion 360 and Rhino/Grasshopper, using modeling operations such as fluting, scalloping, twisting, and lofting to create variations. They pivoted between Fusion 360 and Rhino to "unblock" themselves from the affordances that each CAD environment contained. Due to their goal of producing 100 unique lamps in-house, one of the primary challenges CW&T faced was developing a fast 3D printing process. To address this, they developed custom slicing parameters for each new lamp characterized by continuous extrusion. This custom workflow allowed them to cut fabrication time by 50% over slicer defaults, allowing them to hit their timeline and furthermore have better print success rates. They manufactured each lamp on their in-house 3D printers—Figure 5B shows a partially printed lampshade fabricated on an Ultimaker 2 using their uninterrupted extrusion process. They later added additional printers to ramp up production, resulting in an average production rate of one lamp per day. They repeated their design—production cycle for each new lamp until the production of all 100 lamps was complete.

4.1.2 ListeningCups. Slip Rabbit is a "technoceramics" research studio led by ceramicist Timea Tihanyi in Seattle, WA where visiting researchers collaborate on projects involving ceramics, data, and digital fabrication. The idea for *ListeningCups* came from discussions between Timea and interaction designer Audrey Desjardins on ways of creating ceramic housewares representing datasets of everyday ambient sounds. These discussions led to a week-long residency in which they designed and manufactured a series of 3D printed porcelain cups shown in Figure 1G [20]. Prior to the residency, Timea noted the way interruptions in the 3D printer's continuously extruding toolpath lead to accumulations of clay in a fixed location. They leveraged this behavior as a means of producing the surface texture features of the cup that communicate audio data. Figure 10A shows an in-progress 3D print in which pauses of the 3D printer's toolpath result in bump features. These features could not be represented in CAD, resulting in a design process that occurred exclusively at the level of toolpathing. The initial cylindrical geometry for the *ListeningCups* was exported from a CAD model and converted to 3D printer instructions using slicing software. To incorporate the audio data, Audrey captured decibel levels in different locations. Audrey and Timea imported the data into Microsoft Excel, then used the decibel level to code pause durations in the 3D printer's toolpath. Figure 9C shows an example Excel document with pause durations integrated into machine commands. These pauses were inserted into the printer instructions where they would produce bump textures as the printer continued to extrude without moving in XY. They further developed the design of the surface texture by experimenting with the 3D printer extrusion nozzle and evaluating the resulting 3D printed texture. During the residency they printed, fired, and glazed approximately 20 cups.

4.1.3 CORAIL Table. CORAIL is a collaboration between the high-end furniture company Roche Bobois, the design studio Fritsch+Durisotti, and XtreeE, a company specializing in large-scale 3D printing technologies for materials including concrete, clay, and plaster. All three companies are based in France. The table has a textured 3D-printed concrete base and a glass tabletop, as seen in Figure 1C. The concept arose from Fritsch+Durisotti 's interest in developing a table that customers could customize the form and texture of. The on-demand process was enabled by XtreeE's extensive process prototyping, where they developed a custom printable concrete that relies on a time-sensitive curing process that takes place during extrusion. XtreeE furthermore prototyped custom continuous-extrusion toolpaths that created the intricate layered texture used in the table. To print large-scale objects, XtreeE used industrial robot arms in their own factory. Figure 5C shows the configuration of a robot arm and partially printed table during the concrete 3D printing process. After discussing possibilities with XtreeE, Fritsch+Durisotti produced an initial series of parametric CAD models of table designs in Rhino/Grasshopper. XtreeE used Fritsch+Durisotti's CAD models with their custom CAM software to create robot instructions, both for the robot's proprietary controllers and their own custom mixing and extruding heads. Roche Bobois, the distributor of *CORAIL*, approved moving forward with Fritsch+Durisotti 's designs as a Roche Bobois product. XtreeE 3D printed five prototypes to validate the process. For the customer experience, Roche Bobois outsourced the development of a web customization app that visualizes each table and provides pricing. Customers who wished to customize their table can use the web application, producing a design specification in a custom data structure that XtreeE can directly use for toolpathing and printing. For *CORAIL's* release, Roche Bobois had XtreeE fabricate 100 identical tables to display in their stores. XtreeE stated that since the table's release, customers have only modified the reference design for a quarter of all sold tables.

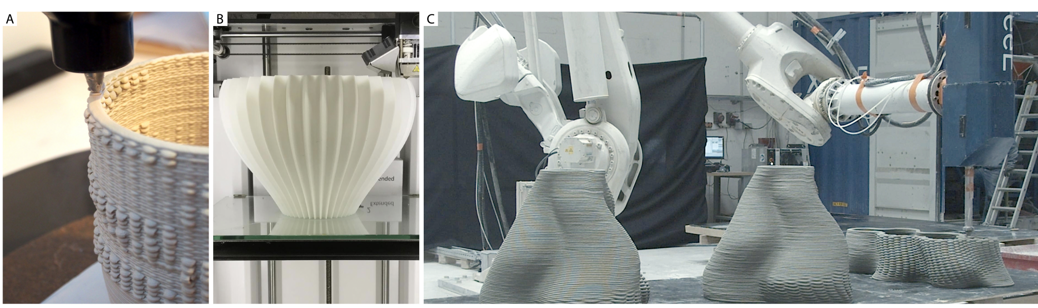


Fig. 5. Shell structures made from continuous extrusion were used at different scales by three of the products we studied. A: ListeningCups in porcelain, B: Dropped Pendant Light in PLA, and C: CORAIL Dining Table in concrete by Slip Rabbit, CW&T, and Fritsch+Durisotti/XtreeE respectively.

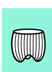
4.1.4 Contrasting Extrusion-Based Additive Workflows. While these extrusion-based additive fabrication workflows shared a common fabrication process, the differences between them, in particular in scale, material, and machine programming, demonstrate how material attributes and machine behaviors play a critical role in realizing specific design and production goals for high-quality custom products. The products were fabricated at distinctly different scales, demanding different machines, expertise, and timelines. The *Dropped Pendant Lamps* and *ListeningCups* were fabricated in build volumes of less than a cubic foot, which made fabrication of these products feasible on tabletop 3D printers. In contrast, the scale of the *CORAIL* table required industrial-scale equipment and with it warehouse-scale facilities and trained robot operators. Each product furthermore was made with different materials—plastic, porcelain, and concrete. Each material has its own requirements for preparation, fabrication speed, and post-processing. For example, different ceramic compositions require custom 3D printing settings and a concrete mixture's cure time places strict constraints on fabrication times. Finally, each extrusion process demanded its own machine control programming. Working with low-level toolpath instructions featured prominently in each of the products in this section, but the reasons and approaches varied. For the *Dropped Pendant Lamps*, a substantial amount of time was spent tailoring the 3D printer's toolpath to ensure a continuous extrusion of plastic; CW&T eliminated any non-extrusion travel of the printhead. This both sped up the overall print process such that they could print 100 lamps for their deadline and removed any extrusion stop/start artifacts that would have detracted from the lamps' aesthetic qualities. For *ListeningCups*, the defining feature of surface bumps was created by editing the machine instructions directly; there was no other way for Timea and Audrey to create this feature. For *CORAIL*, the defining surface texture of undulating lines was also created with a custom machine control process. The *CORAIL* web app enabled customers to visualize the final design, but this visualization was not part of Fritsch+Durisotti and XtreeE's initial design process. Developing each of these workflows relied on high levels of expertise in machines, materials, and CAM. Even if the workflows used off-the-shelf and hobbyist-grade machines, they went far beyond default slicer settings and novice-oriented systems to retain a high level of control over the final products.

4.2 Molding and Casting

Cast objects are made by pouring material into a mold, then curing and de-molding the object. Two of the products we studied used molds as part of their workflow. Rather than using digital fabrication to produce the final pieces, these workflows used digital fabrication—both additive and subtractive manufacturing—to create the molds. Molds can be repeatedly used to produce many instances of an object. While direct digital fabrication enables low-cost iteration of geometry, molds can enable faster production times per object as well as use materials not well-suited for digital fabrication such as glass. For the products we studied, the molds were used for porcelain slip casting and glass blow molding, both well-established methods for producing intricate and delicate objects quickly.

Good mold design was key to the successful outcomes of each product. The participants needed a deep understanding of the casting process to create appropriate molds, including designing mold features such as keys, parting lines, airflow channels, hinges, selecting appropriate mold materials, and ensuring the molds could withstand the temperatures and forces of the casting process. Furthermore, they needed to understand how the surface finish of the mold would impact the surface finish of their final objects, taking into account other processes they would include such as annealing, firing, and glazing. For these products, participants needed both molding and casting expertise and digital fabrication expertise. Both participants consulted mold experts on the materials they wished to work with to develop their workflows.

4.2.1 Coral Cup. Nervous System is a computational design studio founded in 2007 by Jessica Rosenkrantz and Jesse Louis-Rosenberg. They use generative design and digital fabrication to create art, jewelry, and housewares. *Coral Cup* is a slip-cast porcelain cup with undulating surface ridges inspired by natural forms such as coral—the mold components and resulting slip-cast cup are shown in Figure 1D. Nervous System had previously outsourced the production of a prior version of the cup, but they were dissatisfied with the outcomes and wanted a higher level of control in the manufacturing process. They decided to manufacture a new version entirely in-house. Nervous System developed their own computational design software to create the cup's characteristic patterns. Figure 10D shows the textured pattern on ceramic fragments created during testing and process development. Their software allowed them to create reaction-diffusion patterns starting from a range of tunable parameters, which were tested for production by 3D printing small swatches of the diffusion pattern, as seen in Figure 9B. To evaluate which pattern to use, they printed the patterns out on paper and visually inspected them. Figure 9A shows a printout with an array of reaction-diffusion patterns. After selecting a pattern, Nervous System modeled the pattern as ridges on their cup design and 3D printed one full-scale 3D prototype. The purpose of the 3D printed prototype was to validate aspects of the design, such as scale and surface texture, before committing to the time- and material-consuming process of creating molds for the ceramics workflow. Nervous System worked with a ceramics expert to help develop and conduct the porcelain casting and glazing. The workflow consisted of three stages of molding and casting. First, they 3D printed primary molds to cast silicone molds, as seen in Figure 6C. Then, they cast four-part plaster molds in the silicone molds, shown in Figure 6D. The plaster molds were then used to slip-cast the porcelain cups. After de-molding and cleaning, the porcelain cups were bisque-fired and glazed in a kiln acquired for this workflow. Nervous System produced approximately 1000 cups which they sold through their online store, both through pre-orders and after production.



4.2.2 Other Vessels. Path Design is a design studio based in San Francisco. Matt Hutchinson, the founder of Path Design, combines manual craft and digital fabrication to create lamps, furniture, and other design products. *Other Vessels* are a series of five beer glasses created by blow molding glass into CNC-milled aluminum molds. One of the aluminum molds is shown in Figure 6B. Matt created each vessel geometry to correspond to a particular variety of beer. Matt developed software tools both for parametrically exploring design elements and keeping track of functional properties such as the volume of beer the glasses would hold. He used 3D printed prototypes in opaque plastic to validate the scale and form of the glasses. Simultaneously, he took glassblowing classes to learn about the possibilities of the material, experimenting with blowing glass into test molds he CNC milled. Matt extensively iterated in CAM, exploring the way different machine parameters for surface finish impacted the resulting glass. Through this process iteration, he developed methods to create *Other Vessels'* distinctive and aesthetically appealing surface details such as ridges. Figure 6A shows an array of surface details on finished *Other Vessels* pieces. Matt designed CNC milling toolpaths where he used tool stepover and path direction intentionally as a way to create texture. Figure 11B shows the fluted surface texture produced by the aluminum mold in 11C. Matt made five hinged molds for *Other Vessels* using CNC mills at the Autodesk Pier 9 facility and collaborated with local glass blowers to produce the vessels.

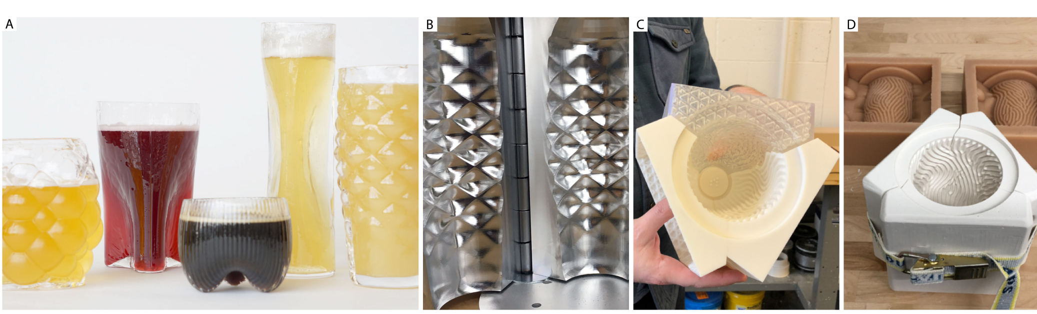
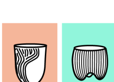


Fig. 6. CNC-milled and 3D printed molds for blowing glass (Path Design) and casting porcelain (Nervous System). A: Other Vessels glassware for craft beer. B: Hinged aluminum blow mold. C: 3D printed mold for casting silicone mold. D: Resulting plaster mold for slip casting (foreground), cast from silicone mold (background). Cast porcelain Coral Cup shown in Figure 1D.



4.2.3 Contrasting Molding and Casting Workflows. Porcelain and glass demand completely different manufacturing processes, even if the design of molds for each material bears conceptual similarities. Even though both products needed to include mold attributes such as keys and parting lines, the heat, moisture, and forces required meant that the material of the molds themselves needed to differ—plaster versus metal. These material differences led to the selection of different processes—additive versus subtractive fabrication. This demonstrates that even conceptually similar processes vary widely depending on materials. Furthermore, both molding workflows relied on materials experts—a ceramist and a glassblowing studio respectively—underlining that beyond digital fabrication expertise, manufacturing also relies deeply on well-established craft knowledge.

CoralCup and *Other Vessels* shared a common need for high standards of quality, precision, and reliability from the molds they produced. For both products, production was halted after an initial run due to a need to address workflow limitations. For Nervous System, this involved moving mold parting lines to facilitate de-molding and cleaning without warping the cups. Path Design similarly needed to adjust their mold parting lines and furthermore needed to accommodate high temperatures, resulting in more complex molds created on a CNC mill with more degrees of freedom. Achieving these high standards required intense periods of process development for both, but the nature of that development varied heavily depending on design and material considerations. These product workflows demonstrate the large time, financial, and educational investments required to produce molds that support multiple production runs of commercially viable outcomes.


Both *ListeningCups* and *Coral Cup* are vessels with textured surfaces made of glazed porcelain. Yet the workflows that led to either product are markedly different—direct additive fabrication versus creating a mold for slip casting. Molds can enable higher production runs by embedding much of the process complexity in the mold, rather than in the resultant object. Indeed, more *Coral Cups* were made than *ListeningCups*. However, each *ListeningCup* is unique and represents a specific fragment of data. These are examples of tradeoffs between direct printing versus casting.

Path Design's CAM work of tweaking and tuning the toolpaths to create surface texture is conceptually similar to the CAM work in the additive fabrication workflows. In all of these products, crucial details of the final model—ranging from surface finish to the form—were never represented in a CAD model. Rather, they came from the purposeful selection of manufacturing parameters such as tool stepover, extrusion parameters, and tool speeds, and were invisible until the products were fabricated. This is an example of how machine expertise informed the product's design. For any of the products we examined, the tradeoffs and design decisions that are made are not always apparent from the final product. We believe these products reflect the broad expertise that was harnessed to make them.

4.3 Subtractive Fabrication Workflows

Subtractive fabrication selectively removes stock material to create an object, for example through milling or cutting. Subtractive fabrication supports a diverse set of materials including wood, metal, plastic, foam, and stone. Machines for subtractive fabrication range from 3-axis CNC gantries to 7DOF robot arms supporting end-effectors for processes ranging from milling to water jet cutting. Material- and machine-dependent aspects of fabrication such as feed rates, spindle speeds, power settings, tool selection, and toolpath geometry are critical for subtractive fabrication outcomes.

Path Design used subtractive fabrication to produce the molds we describe in Section 4.2. In this section, we describe two products that use subtractive fabrication directly for making their products, Filson & Rohrbacher's *AtFAB* and ODK Design's *AESTUS*. Both products use CNC milling of wood and explored the aesthetic qualities of milling details. To do so, they leveraged their expertise in machines, wood, and the requirements and possibilities of creating toolpaths for end mills.

4.3.1 AESTUS. ODK Design is a design company founded by Oliver David Krieg that creates luxury wooden home furnishings through robotic CNC milling. *AESTUS* is a series of wooden vases. Each vase consists of hundreds of layers of stacked wood segments which are milled by an industrial robot arm. Two finished vases with *AESTUS'* characteristic milled textures are shown in Figure 7B. Oliver engaged in extensive software development to create custom simulation and CAM tools for robotic milling. An image of the robot-milling simulation environment is shown in Figure 7A. Oliver produced the vases' primary design feature—non-uniform milled surface grooves—almost entirely through designing toolpaths in his custom software. During the majority of the *AESTUS* design process, Oliver did not have access to a robot arm to test his designs. He spent hundreds of hours developing software to create parametric vase models based on robot arm milling toolpaths. Oliver rendered the resulting structures in V-Ray to simulate what the physical vases would look like. Once satisfied, Oliver contracted a professional carpentry company to mill the vases from glued layers of laser-cut beech plywood stacked on a steel core. Oliver did extensive software development to create the robot toolpath instructions directly from his software tools, which the carpentry company used to fabricate the vases. Figure 1A shows the robot milling process during production.

4.3.2 AtFAB. Filson & Rohrbacher is a design and architecture studio co-founded by Anne Filson and Gary Rohrbacher. They created *AtFAB*, a product that focuses on distributed manufacturing and open-source design. *AtFAB* is a furniture line made of CNC-milled interlocking plywood parts. An example piece of *AtFAB* furniture is shown in Figure 7D. *AtFAB* furniture is available from OpenDesk—a platform that hosts furniture designs and connects customers with fabricators [10]. To ensure viable fabrication, Filson & Rohrbacher created custom software to develop design parameters that would produce reliable joinery in CNC-milled plywood. Figure 7C shows an exploded view of an *AtFAB* table assembly. *AtFAB* used a simple notch joinery detail as a key element of the design—an example of this joinery is shown in Figure 7E. This notch had dogbones, a characteristic CNC milling feature that accommodates sharp corners despite the material being cut with round end mills. Filson & Rohrbacher developed a Processing application that enabled people to customize their furniture within the limits of their design and production process. The application constrains the customer to a predefined range of options for product dimensions, material thickness, and joinery style. Customers can save their customized designs to make on their own CNC mill or select from several pre-designed *AtFAB* furniture models that can be ordered directly without customization through Opendesk. Filson & Rohrbacher receives royalties for each piece ordered through OpenDesk. Filson & Rohrbacher also produced custom *AtFAB* furniture for clients such as Makerbot Industries.

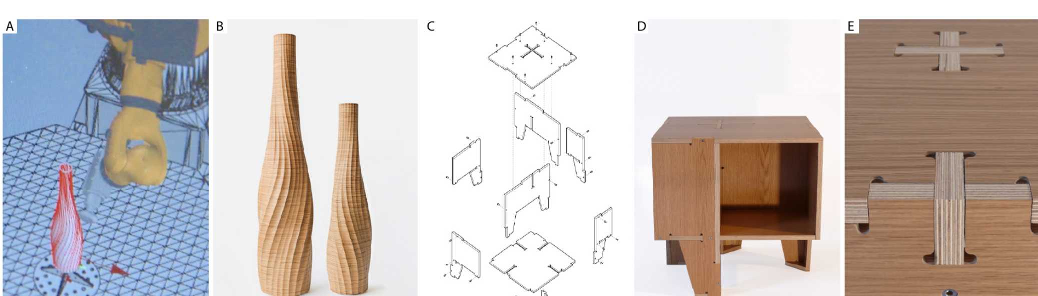
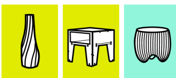


Fig. 7. Both the AESTUS vases and AtFAB furniture used CNC milled wood. AESTUS vases are milled from laser-cut blanks using 5-axis toolpath planning of a donut-shaped end mill on a robotic arm and with a turntable, then sanded and varnished by hand. AtFAB furniture is milled out of plywood sheetgoods on a 3-axis CNC router and sanded and assembled by hand. A: Robot and turntable toolpath planning. B: AESTUS vases. C: AtFAB assembly. D: AtFAB table. E: Detail of the AtFAB joint with the dogbone cutouts that compensate for inner corner radii.



4.3.3 Contrasting Subtractive Fabrication Workflows. For both *AtFAB* and *AESTUS*, CNC milling wood was the main method. Despite this similarity, the machinery, software, fabrication costs, and timescales differed greatly. The workflow for creating *Other Vessel*'s metal molds had more in common with *AESTUS* than *AtFAB*'s did. This demonstrates that similar materials don't necessarily result in similar workflows.

As their material, *AtFAB* furniture used a variety of plywood in standard sheet stock sizes supported by OpenDesk (the company that Filson & Rohrbacher relied on for much of the production and distribution of *AtFAB* furniture). 2.5D milling of sheet stock is a common and straightforward technique, supported by many fabrication facilities including makerspaces [68]. *AESTUS* also started from plywood, specifically a custom high-end lamination of thin beech sheets. But to minimize machining time, Oliver created custom milling blanks using laser-cut pieces stacked and laminated such that only finish-milling toolpaths were needed. Therefore, *AtFAB* furniture can be made at many different sites, while *AESTUS* relies on a difficult-to-reproduce setup. This further highlights how similar materials can nonetheless result in very different workflows—ranging from what equipment was used to how that equipment was programmed and who programmed it.

AESTUS furthermore relied on full 7-axis CNC milling, necessitating access to large-scale industrial robot arms with turntable workpiece holding. Programming 7-axis toolpaths is significantly more complex than 3-axis, and Oliver's design specifically relied on the ability to write toolpaths directly, using an uncommon donut-shaped end mill that would produce the distinct surface texture of the vases. Therefore, he needed to work with a fabrication facility that not only had industrial robot arms but furthermore would allow him to run toolpaths he wrote rather than toolpaths the carpentry generated from a 3D model. Oliver was able to find a manufacturer willing to experiment with him, but their high hourly cost translated to the high prices of the *AESTUS* vases. *Other Vessels* similarly relied on high-end CNC milling equipment and incorporated milling toolpaths as a prominent design feature. To create the metal molds, Matt relied on his unconstrained access to expensive equipment through a specialized residency program and spent a significant amount of his time developing toolpaths. Key features of both products relied on iterating on the manufacturing process—something that could not be done without access to equipment.

Beyond physical differences, all products also featured custom software, but the role and complexity of the software differed dramatically. Filson & Rohrbacher developed a simple customization tool that supported parameterized adjustments such as the furniture dimensions. In contrast, ODK Design invested hundreds of hours of complex software development in order to generate custom robot toolpaths that would create the form of the vases. The different approaches resulted in very different costs and timescales. *AtFAB* could be produced quickly and inexpensively with little oversight from Filson & Rohrbacher by using common materials and machines and partnering with an established fabrication service. Despite their difference in terms of complexity, all products highlight the important role that CAM and toolpathing play in developing a final product, and how control over the CAM process often also implies more control over the production process, necessitating close relationships with manufacturers or even in-house production.

4.4 End-User Customization of Products

Mass-customization has been a widely heralded opportunity for digital fabrication, as start-up costs are lower for unique objects made with digital fabrication. *AtFAB* and *CORAIL* both offer end-user customization of products, in particular adjusting both the size and aesthetic details of the furniture. We included two more companies providing end-user customization in our sample, *WOVNS* and *Weft*. Both produce on-demand Jacquard-woven textiles. Industrial Jacquard looms are large and expensive pieces of equipment; commercial textile mills invest large amounts in their acquisition and maintenance. These facilities rely on large-scale production to offset start-up and maintenance costs, often enforcing a large minimum yardage for production runs and preferring to work with trusted customers who understand the nuances of designing for the looms. Therefore, custom Jacquard woven textile is often infeasible for individuals looking to produce in low-volume. *WOVNS* and *Weft* address this limitation through software platforms that provide end-user customization of Jacquard woven fabrics which can be produced in batched runs of many low-volume orders. Each offers an array of parameters for the customer to explore. These parameters constrain options to make the low-volume production feasible, e.g., through constraining yarn color palettes and weave types. Selecting appropriate constraints is key to making the on-demand services of *WOVNS* and *Weft* viable.

4.4.1 WOVNS. *WOVNS* is an Oakland-based company founded in 2011 by Dena and Chelsea Molnar that sells on-demand Jacquard woven textiles. *WOVNS*'s customers include students, artists, designers, and people who manufacture their own textile products for sale. *WOVNS* provides an online software platform where customers can upload a bitmap image to specify textile colors and patterning, and then order fabric at $45 to $48 a yard. *WOVNS*'s customization platform software is developed in-house. *WOVNS* partners with a textile mill that handles weaving and distribution. Dena designed the *WOVNS* software drawing from her extensive experience as a professional textile designer. She created a digital palette where hex codes correspond to thread color and weave patterning, samples of which are shown in Figure 8C-D. Dena developed a web application that enabled customers to upload design files, select a palette, and place orders for yardage. The mill weaves the orders, performs quality control, and ships orders to customers.

4.4.2 Weft. *Weft* is a company based in Providence, RI, founded by Brooks Hagan and Steve Marschner in 2016. It was awarded an NSF SBIR grant in 2018. *Weft* sells custom woven textiles at any volume greater than 3yds. *Weft Create* is *Weft*'s online software platform that enables customers to interactively customize and simulate woven textiles and then order fabric. Figure 8A-B show the user interface and customization options supported by *Weft Create*. The textile simulation in *Weft Create* is the result of extensive in-house software development derived from academic research published 2008-2012 [45, 46, 104, 106]. *Weft* fabrics are produced at textile mills that specializes in multi-volume production. *Weft* limits designs to high-usage materials to make production feasible. Brooks's experience in textile design and academia informed the concept and user experience for *Weft*'s software. He co-founded *Weft* with computer graphics specialists to develop *Weft*'s textile simulations. Customers upload a bitmap image to *Weft Create*, then select fiber content, yarn colors, and weave structure for different regions. Customers are shown a simulation of their resulting fabric which draws from a database of 3D fabric samples. The simulation can be viewed and interactively altered on 3D volumetric models. The designs are manually reviewed by *Weft* staff, then submitted to the mills. The mills handles weaving, post-processing, quality control, and distribution.

4.4.3 Contrasting End-User Customization of Products. In addition to *Weft*'s and *WOVNS*' customization platforms, *AtFAB* furniture and XtreeE's *CORAIL* table also feature direct, customer-facing software that supports product customization. For each of these end-user customizable products, the designers did not specify a single product, but a design space within which a customer can customize a product. This meant that each company offering end-user customizable products needed to not only develop their products' design spaces but also to develop customers' customization experiences.

We noted a range of approaches in developing customization experiences. Both *Weft* and *WOVNS* relied on in-house software developers to create the customization software and user interface. Filson & Rohrbacher initially developed their customization software on their own but later relied

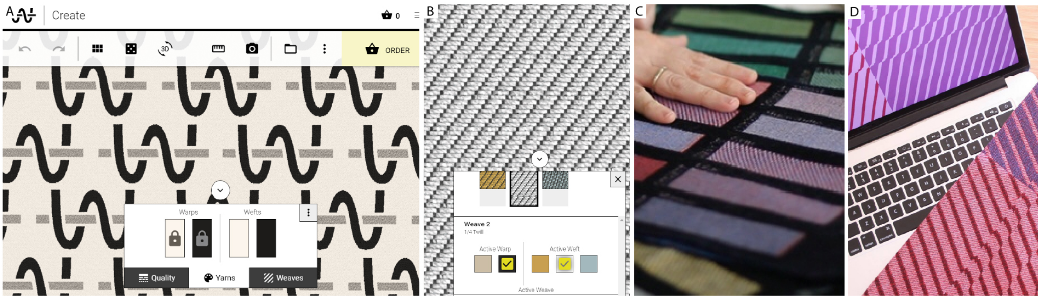


Fig. 8. Both *Weft* and *WOVNS* provide user interfaces for customers to order Jacquard woven textiles quantities starting at one yard. A: The Weft Create interface for uploading artwork and selecting color and weave structure. B: Zooming in on the textile shows a simulation of the resulting weave. C: *WOVNS*'s Talma swatch blanket demonstrating weaves and colors. D: This *WOVNS* textile shows how the weave structure impacts the resulting appearance.

on interns to further develop and refine the interface. For the *CORAIL* table, the development of the customization experience was fully outsourced to a firm specialized in interactive web experiences. Each of these approaches relied on software development that interfaced with, but was still separate from the software that ran any digital fabrication equipment, highlighting the different roles software development takes on in these workflows.

End-user customization impacts distribution models as well as product selection, as each unique product needs to be produced, packed, and shipped to an individual customer. *Weft* and *WOVNS* handle sales in-house, similar to their approach to software development, but can rely on their textile mill partners to ship individual orders to customers. The challenges of customization were also felt at the level of product selection. During the interview, Dena from *WOVNS* commented on how customization and its associated design constraints tend to guide customers toward certain types of products: "Many people just want to upload artwork and don't want to play [with the design software]. They just want it to be cool and woven. The Divan quality [has a fixed number of pattern repeats] and that additional constraint ... turns people off." For *AtFAB*, sales are mostly handled through their partners at OpenDesk, a firm specializing in custom-made plywood furniture, which in turn coordinates production and distribution through their network of fabrication facilities. For the *CORAIL* table, sales and distribution are fully handled by the furniture company Roche Bobois, a high-end firm for whom custom orders are the norm. We observed that the possibilities of mass customization through digital fabrication were being leveraged by the groups we studied, but that these possibilities came together with different and complex needs for sales and distribution.

4.5 Collaboration in Production Workflows

In the nine product workflows we studied, collaboration occurred in different forms and to different degrees. Producing the *Dropped Pendant Lamps* involved no external collaboration—all aspects of the workflow, from design to fabrication, occurred in-house. In contrast, *ListeningCups* were produced as a direct result of collaboration. Timea and Audrey' stated goal was to create a residency through which the two could collaborate on a new project. The production of the *CORAIL Table* was also highly collaborative. Fritsch+Durisotti and XtreeE worked closely to develop technology, methods, and prototypes that were viable for commercial distribution via Roche Bobois. For the remaining six products, collaboration occurred when the production workflow required additional skills or access to equipment and facilities. Jessica and Jesse hired a ceramicist to help develop and troubleshoot the *Coral Cup* production workflow. Oliver and Matt partnered with 3rd party production facilities to gain access to tools and equipment in the production of *AESTUS* and *Other Vessels*, respectively. Both participants remained actively involved throughout the partnership; Oliver operated the robot arm that carved *AESTUS* and Matt took glass-blowing classes to better facilitate a partnership with the glass studio. For *AtFAB*, *WOVNS*, and *Weft*, the product is the design or the service. As such, the forms of collaboration within these workflows resemble a traditional outsourcing relationship in which fabrication of the final artifact occurs through industry partners such as online fabrication platforms and textile mills.

5 CROSSCUTTING THEMES ACROSS DIGITAL FABRICATION WORKFLOWS

Building on our analysis of the digital fabrication workflows of each product, as well as our comparison of workflows with similar primary forms of digital fabrication, we surfaced themes that were shared across companies and manufacturing methods. In this section we describe 1) the role of software development in digital fabrication workflows, 2) how representations used in the workflows only partially described final products, 3) how process prototyping was used to determine viable production strategies, and 4) how designing toolpaths allowed for deeper exploration of material results.

5.1 How Software Development Supports Physical Production: From Scripting to Software as a Product

All of the workflows in our dataset involved some form of software development, which manifested in different forms depending on the company's business model and product. Software development was a critical part of shaping all elements of production, including design activities, the development of fabrication workflows, and the nature of the products themselves. All of the companies we spoke with used computer programming to modify or extend the functionality of existing CAD or CAM tools or automate elements of their design process. We found that many participants used Rhino3D/Grasshopper to develop software for internal use. Rhino3D and Grasshopper conform to the structure of many other CAD tools in that they are designed for extension and feature-integrated programming environments for creating user plugins and libraries, e.g., [39, 56, 67]. As a result, like generic programming environments and languages, practitioners with sufficient programming expertise can extend CAD tools to build a wide range of different applications.[1] In this section, we consider all forms of software development including programming in CAD environments. For example, Audrey and Timea wrote a script to convert their audio data into G-code for clay extrusion and Matt created a Grasshopper definition to ensure *Other Vessels*' geometry conformed to standard beer glass volumes. These approaches facilitated elements of design and production in important ways which we describe in this section.

Over half of the companies we surveyed developed standalone software tools as a primary enabling component of their business model or product.

Nervous System created the *Coral Cup* reaction-diffusion surface pattern using a suite of simulation tools they previously developed. Their concept development and process prototyping were determined by Nervous System's ability to extend their reaction-diffusion software to produce generative designs compatible with a four-part mold with minimally visible mold seams. Notably, they relied on their experience with slip casting to select create final designs, rather than creating absolute constraints in their software.

[1] The frequent use of Rhino3D/Grasshopper in digital fabrication is somewhat analogous to the widespread adoption of Javascript and HTML in web development. Both platforms offer relatively performant development contexts, extensive 3rd party libraries, and high versatility. Given the generic applications of Rhino3D/Grasshopper it is difficult to draw specific insights for systems researchers just from this point alone.

ODK Design's concept and production workflow for the *AESTUS* vases emerged through his development of software for milling with robotic arms in Grasshopper. Oliver's software enabled him to experiment with the effects different toolpaths and end mills had on the vase geometry. Like Nervous System, Oliver built on existing software he had developed through his extensive prior work in robotic timber milling when creating *AESTUS*.

XtreeE developed a software tool for real-time monitoring of the concrete mixing and extruding head they designed. Their software enabled them to follow manufacturing parameters like extrusion pressure in real-time as the robotic arm traced the *CORAIL* table's contours.

These examples demonstrate how Nervous System, ODK Design, and XtreeE could not rely on existing commercial software tools to create their products. Furthermore, in the case of Nervous System and ODK Design, the practitioners' experience and awareness of their software development capabilities directly informed their product concept.

For products with *end-user customization*, software development was a primary enabling component. WOVNS, Weft, Filson & Rohrbacher, and XtreeE developed and implemented customer-facing software that included 1) parametric constraints that applied to a specific product or manufacturing process and 2) a user interface suitable for people without prior digital fabrication or manufacturing experience. In these cases, companies relied on their prior experience with digital fabrication to inform the constraints and interfaces of their customer-facing software tools.

AtFAB's user-facing parametric software emerged from their process of developing internal tools for parametric manipulation of their own digitally-fabricated furniture designs, along with expectations around materials and users. They describe: "We definitely were deliberate [with our app choices]. There were [parameter] sliders, but we knew that you didn't need a 10-foot table. So the slider stopped. [...] Actually, it stopped at the length of plywood pieces, eight feet, I think. So it was constrained by the material. [...] the table height, that definitely got a button because literally there's standing height and sitting seating height. You don't really need that much more than that." This shows how they shaped the user-accessible design space by codifying their fabrication expertise in software constraints.

For the *CORAIL* table, a separate software company developed a browser-based interface for customizing tables. Each table's custom properties were described through a custom data structure that cataloged curves and textures, and parametric constraints prevented customers from designing an unprintable table. For Roche Bobois, having a user-customizable experience created desirable modern and luxurious made-to-measure connotations.

Weft and *WOVNS* relied exclusively on outsourced fabrication for their business model, therefore both companies invested significant time and effort to develop software features that would appropriately limit customer designs to the constraints of a manufacturing and distribution process that they had limited control over. For example, Dena describes how *WOVNS* relies on constrained color palettes: "Woven textile production is very different from print in a number of ways. In woven textile production, the colors have to be constrained because the number of different colored threads is constrained. So someone can't just upload a file with hot pink neon, green, blue, black purple, dusty, pink, rose, and yellow and have it turn out the way that they expected. It's going to be constrained by the colors in the construction. So that's [why] the need for the palettes. The palettes are basically pre-constrained for the user—we're not allowing the maker to make all of those decisions. In order to make *WOVNS* possible, it's auto constrained [...] in order to aggregate." They also developed mechanisms to inform customers about key aspects of the textile weaving process, either through tutorials in the case of *WOVNS* or in-software simulation in the case of *Weft*.

These user-customized product examples demonstrate how, like other forms of end-user software developers, digital fabrication practitioners invest significant time and effort in refining software for broader use [49]. However, in addition to engaging in debugging, testing, verification, and documentation to ensure general usability, practitioners with customized products faced the added requirement of conveying manufacturing and material limitations and affordances through the software user experience. Their ability to communicate the design space of a product to a non-expert customer base directly determined the degree to which they could deliver refined and distinctive products.

Both examples—internal and customer-facing—show how software development played a central role in the design and manufacture of products in low-volume, and how all practitioners went significantly beyond existing features in commercial CAD and CAM tools. This indicates that beyond expertise in design and fabrication, the participants also needed some amount of software development expertise. Their software was often conceptually similar but practically very distinct, e.g., converting data to niche file formats that were appropriate for specific pieces of digital fabrication equipment. Beyond software developed for design and manufacturing, these cases also demonstrate how business models that center on product customization additionally require different forms of software development labor to create customer-facing experiences. This is in contrast to software development for internal design and production workflows, or as Nervous System put it, "whenever we make anything for ourselves, we make it the laziest possible way and it's much harder to use."

5.2 How Designers Rely on Multiple, Partial, and Ambiguous Representations

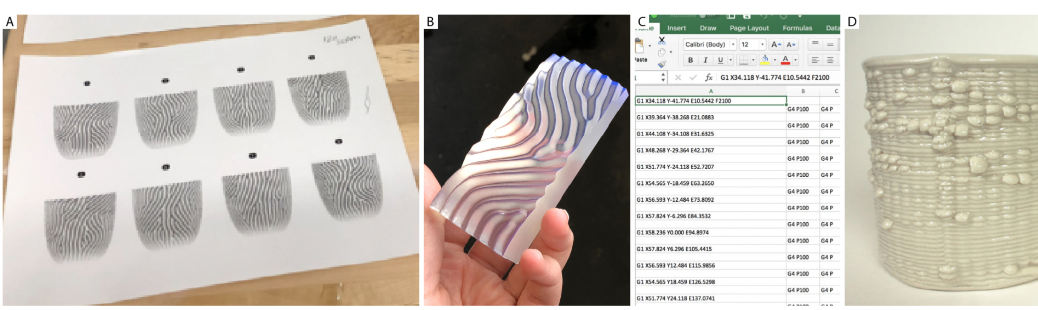


Fig. 9. Participants used highly abstracted design representations. A: Nervous System selected their coral patterns just from 2D images. B: To test the Coral Cup's ridge heights, they 3D printed small swatches. C: the ListeningCups' bumps were only captured in G-Code that Slip Rabbit edited in Excel. D: Audrey and Timea 3D printed their G-Code directly to evaluate its properties. In an early test, they noticed that their approach introduced an unwanted seam. To correct this, they re-sliced and then reintroduced the bumps.

As the Nervous System quote above suggests, participants often relied on partial design representations when making their products. Some of the manufacturers we interviewed relied on abstracted design representations, such as machine toolpaths and 2D images. For example, Nervous System reported using 2D black and white images of reaction-diffusion patterns as part of their pattern selection process. They describe: "We do a lot of just printer prototyping, printing [...] with a black and white laser printer. I print up tons of sheets of paper with views of things from different angles at scale and look at them—that's quick and easy and cheap." Timea and Audrey manually edited G-Code to create the cups' texture without knowing exactly how their changes would affect outcomes. Audrey explained that "in the beginning, it was kind of just a shot in the dark based on Timea 's experience. And then after maybe the second day or the third day, we could make decisions based on what we had just printed." Similarly, Matt could not rely on digital models to characterize and design the surface textures of *Other Vessels*, which were a product of specific milling parameters. In fabricating each glass, the texture patterns were not fully understood in advance, resulting in aspects of the design that were more emergent than prescribed.

For some participants, physical representation was an important aspect of the workflow, even if physical prototypes were not high-fidelity or the final forms. For example, Path Design's glasses were initially 3D printed with black opaque plastic. These prototypes shared none of the material qualities of the final glasses which, for Matt, was "absolutely fine. It's about the surprise when it first comes out of the mill, which is like nothing you might expect." For CW&T, prototypes were created in the flow of design and production, as a way to validate both design and extrusion settings.

In all of the above cases, production began without a complete simulation of the end result. Instead, the aesthetics and functional aspects of the product were worked out in the manufacturing process. What enabled participants to move confidently into production with only partial representations of their products was often prior knowledge of materials, machines, and fabrication processes. This manufacturing expertise allowed them to envision the outcome of their workflow without fully simulating it computationally.

5.3 How People Develop Robust Product-Specific Manufacturing Workflows

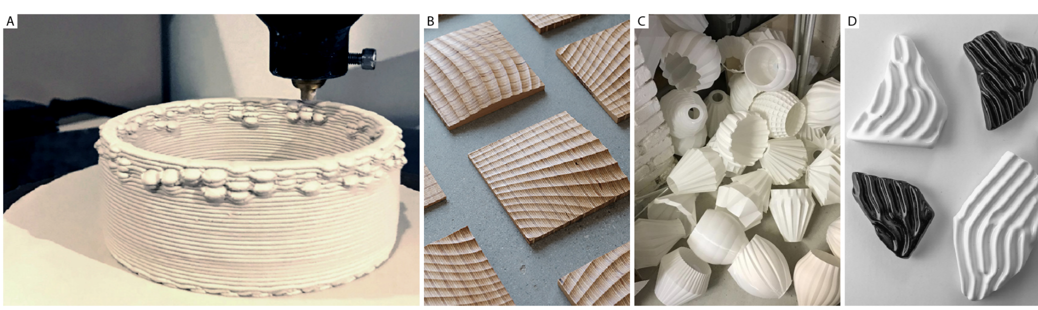


Fig. 10. Manufacturing process development such as selecting end mills, nozzle sizes, and firing temperatures factored heavily into the product outcomes. A: Pause timing and nozzle size created the unique surface texture of ListeningCups. B: Determining the milling speeds for the specialty end mill in beech plywood enabled ODK Design to create crisp and smooth textures that did not need additional sanding. C: CW&T developed a combined slicing profile for their lamps that optimized for high speed and low internal artifacts. D: Coral Cup's ceramic production relied on tuning glaze recipes and firing schedules.

We found that beyond objects such as code or physical prototypes, practitioners relied heavily on prototyping fabrication *processes* to create viable production workflows. This form of prototyping activity, categorized as *process prototyping* in our analysis of workflow steps, included experimentation with materials, machine behavior, and the integration of digital fabrication techniques with manual forms of making. In process prototyping, practitioners revised production steps and designs in response to experience gained when working with materials and fabrication equipment. The production processes the participants arrived at shaped the aesthetic and functional features of the products as much as decisions made in software. In each of the examples below, defining features of the product—surface texture, manufacturing rate— came from production processes customized to materials and equipment. These material qualities were not present in software representations prior to production and, in some cases, required the practitioners to learn new ways of working with software, equipment, and materials.

For example, process prototyping for Audrey and Timea resulted in key design features that weren't present in the CAD model or G-Code of *ListeningCups*. After creating the G-Code files for the ceramic 3D printer, they experimented with machine-specific choices such as the extruder's nozzle size. Timea described how these choices played a crucial role in determining design features such as "how big the bumps [were]" and "how thick the wall [would] be." The same G-Code file could produce many different iterations due to machine settings and material choices.

Oliver from ODK Design tested various end-mill shapes and milling speeds on small wooden tiles to ensure crisp lines and minimize post-processing. The tiles also served as pattern samples and helped Oliver get a sense of the different aesthetic effects the milling paths could produce. Similar to Slip Rabbit, he iterated with his machine tooling choices to explore different aesthetic outcomes.

Process prototyping also played a critical role in determining the rate and cost of production. For example, to reduce the milling time by professional woodworkers using an expensive industrial robot arm, ODK Design started from laser-cut plywood shapes stacked around a steel core. This, in combination with his custom robot toolpath planning software, reduced the amount of material the robot arm removed to just a few millimeters of undesirable burnt edges (Figure 1A) while still achieving a crisp continuous final line (Figure 10B). This limited the number of expensive milling hours needed for each vase.

Production time was also critical for the Dropped Pendant Light. Early in their workflow, CW&T determined print settings that optimized the speed and success of printing by relying on continuous extrusion. "All the final lamps are a single path [...] so the extruder never stops extruding. The first few ones that we designed that wasn't a constraint, so the extruder would stop extruding and have to travel and then start again. And so you would get some weird artifacts on the side, like the little loops where it stops extruding and starts extruding. And it wasn't very efficient and sometimes the prints would fail. There were all kinds of issues. [...] Pretty early on, maybe like after the fifth or sixth design or print, we were like, ah, that's no good. We have to make it so that it's a single extrusion all the way." This subsequently influenced their design decisions: "[Prints] would fail for various reasons, like under extrusion or coming off of the plate or sometimes our overhangs are too big, stuff like that. So that's the kind of learning that would happen. And they would become constraints on the model. Not any kind of numerical constraints, but just a feel for like, oh, we shouldn't be overhanging as much. Or, and then also in terms of print settings being like, if we are [overhanging] this much, we really got to slow down the print so that it cools off by the next time it comes around. Stuff like that."

Nervous System hired a formally trained ceramicist to help develop and prototype the ceramics manufacturing processes for Coral Cup. They repeatedly revised manufacturing methods throughout their production workflow to address the realities of working in porcelain. Jessica described how issues included "bubbles in the slip...contamination in the slip...warping in the cups once they're de-molded" and "issues with the glaze." These production details could not have been accounted for in software representations of the design. The level of control Nervous System gained through process prototyping was a determining factor for creating a high-quality product. This control was only feasible because they had direct access to and control over their means of production.

Process prototyping with digital fabrication tools required repeated iterations jumping from software definitions to physical features and back. Here the participants were identifying feedback loops between digital decisions and real-world outcomes, leveraging expertise from both domains. The resulting products are beautiful and durable in ways that would be difficult to achieve when sending design files out to manufacturing services without the chance to fine-tune. Even the low-cost hobbyist equipment some of our participants worked with did not detract from their final products due to their intensive process development.

5.4 How Machine Toolpaths Are Design Choices

Although creating digital models of products in CAD software was a feature in all of the workflows we studied, we found that participants also developed critical features by designing and optimizing toolpaths. We found evidence of direct toolpath design in a range of fabrication methods, from specifying slicer settings in off-the-shelf software to hundreds of hours spent on software development for creating custom toolpaths. Participants featured toolpath control in marketing material for their products—emphasizing how digital fabrication machines are part of the product's story. Making design choices through the control of toolpaths resulted in design outcomes that could not be planned, controlled, or even represented in CAD.

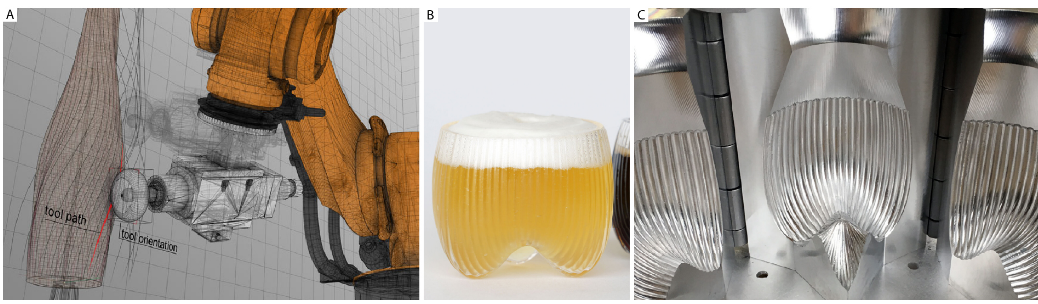


Fig. 11. Toolpaths were used by multiple participants as distinct design elements of their work. A: The geometry of AESTUS vases came entirely from the toolpaths and tool orientation. The vase emerged from the cutting lines, one of which is shown in red. B: One of the Other Vessels glasses relied on widely spaced toolpaths to create a fluted texture. C: The blow mold used for creating the Other Vessel in B.

To create the primary design feature of the *ListeningCups*, Audrey and Timea generated G-Code with slicing software and manipulated the resulting extrusion toolpaths by directly editing toolpath pauses into the G-Code in Microsoft Excel. Extrusion continued during these pauses, resulting in "bumps" that functioned as a data visualization of previously recorded sounds. The resulting surface textures from the inserted toolpath pauses were only represented in G-Code and printer behavior. To refine their approach to G-Code editing Audrey and Timea created test prints to explore the way different pause durations and sequencing of toolpaths with and without pauses produced different design qualities.

Path Design used commercial 5-axis CAM software for the design of *Other Vessels*. While prototyping the glassblowing process, Matt observed how ridges and lines from the milled surface of the molds transferred to the surface texture of the glass. Rather than minimizing this effect, he programmed widely spaced toolpaths to create a fluted texture that would transfer to the glass while minimizing parting lines. This texture is not captured in the CAD model but came from Matt designing in CAM. He describes: "The [surface fluting on the snifter glass] is a single pass going a negative increment into the finished surface. That one was just probably my favorite glass because it was something that wasn't even visualized in the software at all. [...] The texture that comes out of that is something you don't see it until the glass is done."

Milling toolpaths were a design inspiration for *AESTUS*. The possibilities of this process were in fact specifically what he sought to explore: "The main motivation was exploring the milling paths on wood material and especially parametric parts [...] I found that there was an aesthetic language that hadn't really been explored so far, particularly because it's not something you actually 3D model. It's something that you designed by designing the milling paths themselves and see what the result looks like. And so I found that very intriguing." To explore this design space, Oliver developed his own software to create custom 7-axis robotic toolpaths. The industrial woodworking company he partnered with normally generates toolpaths for their clients, but in this case, made an exception to run his robot instructions.

Here practitioners relied on directly manipulating toolpaths to create important design features of their products or even define the product geometry in its entirety. Rendering tools were unavailable or gave low-fidelity approximations of the results. Our participants' access to and familiarity with digital fabrication equipment made it possible for them to anticipate outcomes despite the lack of simulation of results, but ultimately they relied on process prototyping to make informed design decisions.

6 DISCUSSION

In our first research question, we sought to explore the real-world workflows of people who use digital fabrication to manufacture products. We found that software development featured strongly and that intermediate design representations gave only partial shape to final outcomes. We also observed that process prototyping was necessary for successful manufacturing and that machine toolpaths themselves were not just compiled but actively authored. In our discussion, we address our second research question: How do existing digital design and fabrication technologies enable or limit the design, manufacture, and sale of customized products?

6.1 Parametric Design Should Support Exploration of Geometry, Machine Settings, Material Behavior, and the Interdependence Between the Three

Parametric CAD models provide an opportunity to explore design variations in ways that avoid destructive editing while preserving design intent. Designing with parametric models is most commonly used to constrain geometry in the domain of digital fabrication. HCI researchers have developed tools that allow users to manipulate parameters of algorithmic processes in order to generate geometric features. Recently, these researchers have oriented parametric design tools around producing geometries that support specific forms of viable fabrication outcomes. In [29], parametric tools constrain the endless possibilities of virtual geometries to be compatible with physical materials and craft making. Mueller et al. [71] demonstrates parametric tools that alter geometry in order to increase the speed of rapid prototyping. Parametric machine learning tools have also been developed to generate geometries for domain-specific fabrication tasks, such as custom electronic components [79]. While these examples ensure that geometries are viable for specific digital fabrication contexts, the parametric aspects of the design tools do not directly control parameters of fabrication machines and processes.

Our analysis of professional digital fabrication workflows showed that parametric CAD is an important design tool; however, professionals apply parametric design in ways that go beyond varying geometry. We found that professionals just as often wrote code and software that parameterized the *behavior* of CNC machines. Parameterizing CNC machine behavior allowed our participants to explore the way variations in toolpath settings, material deposition rates, and geometric slicing impact the product's design. Changing machine settings for digital fabrication machines is currently tedious and typically requires the use of machine-specific interfaces that are not directly integrated into the software our participants used to explore geometric parameterization. Despite the extra effort required, exposing and parameterizing machine settings allowed our participants to explore new fabrication processes (*ListeningCups*'s pauses in deposition), develop original aesthetics (surface textures for *AESTUS*, *Other Vessels*, and *Coral Cup*), and optimize production for efficiency (custom geometry slicing to decrease print times for *Dropped Pendant Lamp*).

Furthermore, when creating parametric CAD models, professionals developed the most effective parametric representations *after* they had direct experience exploring settings for machines and materials. For example, after initial printing, CW&T constrained their designs to maximize speed and quality. Nervous System optimized their reaction-diffusion patterns for the constraints of slip-casting molds. *Weft* and *WOVNS* constrained their color palette and weave structure options based on their experience with industrial Jacquard looms. The constraints in the *CORAIL* table web customization application were the result of XtreeE's prototyping and manufacturing validation process.

Our research shows that professional designers develop parametric relationships in software that allow them to explore different machining methods for materials used in their production workflows. These findings are aligned with recent digital fabrication systems research aimed at providing parametric control over machine behavior within the same software interface that supports geometric parameterization [31, 94]. These systems enable incremental exploration of machine behavior to inform decisions made during the design process—as opposed to systems that support designing arbitrary geometries followed by tools that generate machine toolpaths for fabrication.

Our research suggests opportunities for continued work in this space. Further integrating CAD and CAM could enable parametric control of material properties, e.g., varying extrusion rates to vary rigidity in 3D printed parts, varying toolpath acceleration to vary milled surface textures, and selectively applying glaze based on surface measurements. These forms of material parametric control, utilized in tandem with geometric and machine parametric control, were used in the workflows developed by our participants. Future systems that embrace the strategic exposure and control of machine settings could support less experienced makers by facilitating the exploration of the interdependent relationship between geometry, materials, and machines, which is crucial for successful outcomes in digital fabrication.

The role of machine and material behaviors in parametric design also has implications for developing customizable products. The end-user customization component of products such as the *Dropped Pendant lamp* and *AtFAB*'s furniture was underutilized or unsuccessful, in part, because customers lacked the required experience or knowledge of material and machine behaviors. For instance, the STL files of the *Dropped Pendant Lamp*, made available to customers wishing to print their own, do not communicate the custom slicing settings and continuous extrusion modality developed during CW&T's production workflow. Customers are not expected to have an understanding of the manufacturing process, yet this process determines high-quality product outcomes as much as the geometry does. This tension suggests that, for customers, customizable parametric products that only incorporate constraints or guidance on geometry without factoring in material or machine constraints might result in a wide variety of outcome qualities. Depending on the complexity of the fabrication method, customers would need to develop their own knowledge and command of material and machine behaviors in order to ensure outcomes on par with those of professionals. CW&T saw little evidence of people printing their own lamps despite the STLs being freely available. This is in line with the work of Oehlberg et al. [75], who found extremely limited use of parametric geometric models in the Thingiverse online maker community. Similarly, Filson & Rohrbacher discussed how few, if any, *AtFAB* customers utilized their customization app—opting instead to order their standard furniture designs through Opendesk. *WOVNS* and *Weft* achieved more success in creating customizable products, in part by exposing aspects of their manufacturing process. Their approach sought to inform customers and provide low-level control over aspects of material behavior and the relationship between weave structure and visual and tactile qualities in the textile fabrication process. Moreover, most of *WOVNS* and *Weft* customers were designers or students in design. They were therefore knowledgeable users who could receive the information presented on the companies' platforms and use it to make informed design decisions about their customized orders.

For products that feature end-user customization, we argue that future digital fabrication systems research needs to expose and provide control over the interdependent relationships between geometry, materials, and machines in digital fabrication in order to support high-quality outcomes. Supporting explorations of these interdependent relationships would provide a way for new entrants to learn digital fabrication in a more holistic way that reflects the realities of designing products for fabrication via CNC machines. This is especially true for customizable products given the information loss that often occurs when complicated production processes are abstracted and only geometric parameterization is available.

6.2 Process Prototyping is Critical, Simulation is Not

Personal fabrication is a vision of digital fabrication wherein people with little to no prior digital fabrication expertise design and produce physical objects in their own homes [33]. Personal fabrication has been adopted as a primary motivation for much of HCI digital fabrication research, where the objective of digital fabrication technologies is characterized as the ability to "create objects instantly" in a manner comparable to the generation of digital objects in fields like augmented and virtual reality [27]. Framing future of the digital fabrication through the metaphor of digital rendering is at odds with the reality of digital fabrication practice because it obscures the interdependence of *process* and *design intent*.

Our research shows how digital fabrication product manufacturing and product conception are inseparable; the success of the products in our dataset did not hinge on isolated critical competencies that aligned with discrete steps in production. Rather, participants conceived of their products largely *as workflows*. They demonstrated an understanding of how individual steps were interdependent, they anticipated challenges as they envisioned product form and function, and they strategically invested time working out critical elements of the full workflow. For the CORAIL table, this meant Fritsch+Durisotti and XtreeE communicated early on about the design affordances of XtreeE 's concrete 3D printing. With an in-depth understanding of this novel manufacturing process, Fritsch+Durisotti were able to constrain their designs to ones that XtreeE could manufacture. Furthermore, they incorporated new process-specific opportunities into their designs, such as introducing texture with wavy toolpaths. These constraints were codified in a custom data structure describing each unique table. This close collaboration between the designer and fabricator was necessary to arrive at the table's design.

To give another example, CW&T only designed and printed a few lamps before launching their Kickstarter campaign and committing to fulfillment. Despite being experienced with 3D printing, they anticipated the printing process to be a potential hurdle for the lights, which is why they fully tested their 3D printing process before launch. They were confident that if their computer-controlled manufacturing processes worked, they could handle the design and distribution elements of their workflow, even if that meant that design work would be happening simultaneously with production. CW&T and XtreeE were not alone in their ability to envision workflows that spanned design and manufacturing. All participants conceived of manufacturing methods that would support specific product features early in their design process. This is in contrast with traditional manufacturing, where R&D and manufacturing are distinct, and also in contrast with visions of personal fabrication in which end users fabricate customized products by specifying high-level design intent with no knowledge of fabrication processes.

Furthermore, participants did not separate design and production steps but rather explored the interdependencies of the two. Critically, that meant understanding how choices made in software influenced particular physical features. To better explore specific manufacturing elements, they developed software. To better understand software constraints, they conducted manufacturing tests. It is worth noting that iterative processes are by no means unique to digital fabrication workflows.

In entirely digital domains, such as software development, creators frequently employ iterative development and testing strategies [59]. We argue that process prototyping in digital fabrication is different from digital-only workflows because it incorporates iteration across physical processes that are only partially represented in software, or in some cases not represented at all—as we saw with Oliver using a rough simulation of his vases that only partially reflected the fabricated outcome and Timea and Audrey only representing their cups in code prior to printing.

Rather than digital-only workflows, we argue that process prototyping in digital fabrication is more closely aligned with iterative methods from craft and design. In theorizing workflows, Ingold and Schön have respectively described how design ideation is directly shaped by material engagement [41] and iterative design processes [87]. Ingold specifically argues against a paradigm where making involves imposing form on the material world (hylomorphic model) and instead suggests that form emerges from engagement with materials (morphogenetic model). Our findings reinforce Ingold and Schön's theories by demonstrating how the products we studied are developed by people who understand the constraints and affordances of fabrication methods, materials, and processes. In the case of our participants, their ability to envision software, machine, and material interdependencies created key opportunities for making unique and valuable products: the new forms of vases and cups, custom and customizable lamps, tables, and textiles. Our participants were able to conceive of products that initially might have been considered impossible to manufacture and to manufacture things that were difficult to represent as CAD models.

In section 6.1, we described the importance of integrating machine and material exploration in parametric CAD. Digital simulation theoretically offers the possibility to engage in such exploration without the perceived challenges of working with real materials and machines. Simulation played a role in some aspects of participants' workflows and represents a meaningful aspect of digital fabrication as a whole. Yet simulation alone cannot act as a substitute for process prototyping. Simulation reflects established models of fabrication processes. Our participants developed novel fabrication processes and therefore could not rely on existing simulation tools. Creating robust simulations of novel processes would present a non-trivial engineering effort without clear benefits for our participants. It was more efficient for them to invest their time in process development because it simultaneously enhanced their design knowledge and produced physical outcomes.

Moreover, the design knowledge that emerged from process prototyping served as a competitive asset for our participants because it allowed them to conceptualize feasible and novel future products. Because participants had the capacity to understand interdependencies of digital and physical design, they were able to predict aspects of cost, labor, material usage, and key product features prior to developing and executing the entire product workflow. This capacity is a critical advantage in low-volume production scenarios where margins are narrow, quality expectations are high, and creators often have a limited startup budget. The utility of digital simulation is limited by comparison because it fails to represent a wide array of design spaces and variations in the manufacturing approach. While it is theoretically possible to simulate multiple dimensions of a process including manufacturing outcomes, cost, and labor, it is difficult to envision a practical system that could adequately represent the design knowledge of the individuals within our study. If we are to support more creators with low-volume production, we must accept the limitations of simulation to represent novel product manufacturing processes and consider alternative strategies.

6.3 We should develop tools that support users' continuous need to learn new tools and techniques

Our study highlights how interdisciplinary learning played a prominent role in enabling digital fabrication professionals to design and produce custom products. While the participants in our study demonstrated expertise in some aspects of design and fabrication, they were also initially inexperienced in other aspects of the workflows they developed. For our participants, learning how to extend their expertise to new materials and fabrication processes was a crucial aspect of their production process.

For example, Matt from Path Design was new to working with glass and took glassblowing classes to inform his design and production workflow. Similarly, Nervous System hired a ceramics expert to advise them in developing slip-casting workflows that could support the intricate design of their cup. Several participants, including Filson & Rohrbacher, Audrey and Timea, and *WOVNS*, learned software development skills to support the forms of customization that were crucial to their products. Participants also learned new skills when developing new, product-specific workflows. This often occurred at the intersection of CAD and CAM, where integrated knowledge of specific materials and machine behavior was crucial for producing complex, custom, and idiosyncratic products. For example, CW&T learned new modeling methods and additive toolpathing approaches as a direct consequence of the requirement that they rapidly produce 100 unique and robust 3D printed lights. The prevalence of learning activities in our participant's product workflows reinforces how learning is a continuous facet of low-volume digital fabrication production and is not limited to inexperienced practitioners of digital fabrication.

Understanding how digital fabrication professionals learn new skills is useful for research that supports experts. However, we argue these findings are also applicable when researchers are interested in supporting new entrants in digital fabrication. Prior research into supporting learning in digital fabrication has often been aimed at inexperienced practitioners. These individuals, characterized as novices, amateurs, or first-time users, were found to have difficulty producing models viable for fabrication, especially if any forms of customization were introduced. In response, HCI systems researchers have developed design systems and software tools that simplify and automate aspects of digital fabrication. Prior work in this space has included automating the generation of fabrication files from 3D models [9, 90], constraining design spaces to components that are viable for fabrication [91, 102], and scaffolding the design process with examples from experts [54, 88]. Often, these systems and tools intervene at the interface of CAD and CAM, alleviating the need for individuals to have in-depth knowledge of materials and machine behavior to fabricate their designs. Similarly, they aim to reduce the exploration that occurs in the physical realm by constraining the design space in software to ensure successful fabrication outcomes.

Our study shows that experienced digital fabrication practitioners faced difficulties that in many ways align with the challenges that motivate the design of tools for "novices." Professional fabricators dealt with machine and manufacturing errors, repeated iterations at the physical production stage, and grappled with adapting digital designs to material constraints. This finding challenges the validity of drawing stark boundaries between the needs of novices and the needs of experts in digital fabrication systems research.

Our participants overcame these difficulties by gaining greater knowledge of complex digital fabrication tasks, as opposed to automating and simplifying complex tasks. Working with tools that automate and simplify digital fabrication might have reduced the need to learn new skills but at a cost. Because such tools constrain the design space, they prevent more customized product outcomes. Moreover, by emphasizing models that fit a clear set of fabrication constraints, these approaches limit the degree to which creators can discover and understand design opportunities that emerge from the combination of specific materials and approaches to machining. Many key features of our participant's products were a result of understanding and exploring complex aspects of machine and material behavior during fabrication, rather than in software alone.

The high degrees of learning demonstrated by our participants suggest an opportunity for systems researchers to expand prior novice-oriented digital fabrication tools by supporting learning outcomes at all levels of expertise. New systems could go beyond automation and simplification by scaffolding learning of both introductory and complex aspects of digital fabrication workflows—such as programming machine behaviors, prototyping fabrication processes, and error detection. A systems research approach that scaffolds learning in digital fabrication could mirror approaches in domains of HCI that identify and address challenges faced by end-user programming, such as tools that scaffold program understanding [12, 76]. As opposed to tools that use automation to limit the need to program [37, 42, 47], tools that support learning complex tasks, such as debugging, enable users to develop new skills and create idiosyncratic rather than pre-defined outcomes. A similar approach in digital fabrication systems research could support the types of learning demonstrated by our participants. Our study shows that, like inexperienced individuals, experienced practitioners of digital fabrication seek out learning opportunities to develop new and complex skills. By developing these new skills, our participants were able to develop custom workflows that were essential to creating their products. It's possible that these approaches may not be of interest nor suitable for individuals pursuing hobbyist forms of digital fabrication, nor would they necessarily increase the overall "ease of use" of digital fabrication technologies. Instead, such approaches could aid in helping new practitioners develop both skills and creative insights necessary for the design and manufacture of novel and high-quality digitally fabricated goods.

6.4 Material constraints and resource management are design dimensions to support, not realities to flatten or optimize

A particular vision of digital fabrication within HCI emphasizes the immediacy and labor-saving opportunities that computation enables for fabrication. However, our analysis made clear that regardless of promises of increased precision and automation, digital fabrication processes remain resource- and labor-intensive. The allocation of these resources, including time, money, materials, and cognitive/physical labor is, therefore, an important factor to take into account when designing systems for digital fabrication. We found these dimensions were not extraneous to the fabrication processes but constitutive of them, and determined the aesthetic, functional, and commercial qualities of the final products we studied in important ways. The professional designers and manufacturers we interviewed showed that their technical and material skills enable them to competently allocate these resources in a way that was sustainable for their aesthetic and commercial goals.

The way in which digital fabrication is different from traditional craft is not because digital fabrication processes are always more streamlined or more precise than craft, but rather that designers are now also working with code—information made visible. Specifically, digital fabrication involves what Shoshana Zuboff called "informating" in the late 1980s: the process by which information technology translates objects, activities, and events into information [108]. Digital fabrication systems turn design *and* the technical gesture into information. This information can be shared, extended, or modified, but it is also incomplete. Our data shows that despite the increased visibility and "prehensility" of design information in digital fabrication, as well as the increased precision afforded by digital machines, digital fabrication workflows remain subject to very material and situated constraints.

The fabrication processes developed by the participants were not shaped by design intent and access to machines only but by factors seemingly external to the workflows themselves: time frames, commercial infrastructures, access to tools and knowledgeable colleagues, and opportunities to address gaps within existing manufacturing services.

These extrinsic factors influenced internal workflow considerations such as choice of tools and materials, fabrication technique, as well as design decisions. For example, the glasses of Other Vessels were shaped partially in response to what Matt was learning about glass blowing and the possibilities of CNC milling. The final form of the molds made by Nervous System was shaped by the need to find a more efficient and reliable demolding process that could meet the demands of an intensive commercial production phase.

Moreover, the workflows described in this research are resource intensive in part because they are unique, leveraging design and manufacturing expertise to create objects with distinct aesthetic and functional features. Contract manufacturers using digital fabrication tools might not need to develop unique processes to manufacture distinct objects, relying instead on tried-and-tested workflows. Nervous System initially tried to outsource their manufacturing process for the Coral Cup but they were unsatisfied with the results. To have more control over the design and fabrication process, and to create cups that met their aesthetic standards, they developed their own process and created a unique product. The future of distributed manufacturing depends on the consideration that digital fabrication workflows are often developed in response to very specific sets of motivations, design goals, technical constraints, and commercial or material opportunities, among others. The interdisciplinarity and variety of digital fabrication endeavors mean that there is no one-size-fits-all approach when it comes to workflows. Instead of flattening workflows into a set of predetermined steps, researchers would gain from developing systems that can support the unique combination of specific techniques, tools, and skills present in each digital fabrication project.

Many of the promises of digital fabrication, e.g., increased precision, rapid prototyping, streamlined workflows, and automation, evoke a future for small-scale manufacturing where resource management is optimized and labor minimized. Instead, the participants we interviewed talked about making decisions that balanced not just the considerations of manufacturing skills and design knowledge but also the demands of technique acquisition, tool access, time allocation, and financial resources. These decisions were not compartmentalized but instead understood together as part of the same chain of operations. The efficiency and viability of these workflows were achieved through an understanding of how these factors worked together (and when they did not).

Even with increased precision and automation, fabrication processes remain cost and labor-intensive. Moreover, fabrication workflows are rarely —if ever— shaped by intrinsic motivations alone (design intent) but constantly adapting to external factors such as the availability of tools and materials, encounters with mentors, course offerings, learning of new fabrication techniques, and commercial infrastructures and opportunities, among others. The management and allocation of these material, commercial, social, and technical resources are not things to abstract from fabrication systems or to optimize for; they are design dimensions that need to be accounted for in systems research.

7 CONCLUSION

Front's 2005 performance of sketched chairs highlighted many promises of digital fabrication. It also exemplified the idea of digital fabrication as compilation: draw or think up almost anything and the machine will make it—much like the "matter compilers" described in science fiction [93]. The Swedish studio's performance furthermore echoes a focus on digital fabrication research in HCI, which seeks to bring more expressiveness to digital fabrication systems. This expressiveness is often emphasized without considering *how* things get made.

Our research shows that how things get made is not simply realizing a digital design and that creative decisions do not get made in CAD alone. Rather, our survey of nine digital fabrication workflows demonstrates that low-level machine behaviors and material properties are the cruces of expressiveness for products made or customized with digital design and digital fabrication.

We inquired about the design and manufacturing of nine products, and we saw that designers conceived their products at the same time as they did their workflows. The result and the process were entangled throughout the workflow steps. Our participants were creative and expressive not only with the geometry of their products but also with their materials, the machine processes that made the products, and the combination of these three elements in a workflow. For digital fabrication systems to support the making of expressive *and* viable products, we need to expose the parameters where critical design choices get made—not only geometry but also low-level machine controls and material behavior.

Access and education also play a role in the workflows we observed. Prior to conceiving and developing these products, our participants had amassed hundreds of hours of exposure to digital fabrication tools and spaces, often by virtue of professional training or higher education. This exposure was an essential factor in their ability to develop viable workflows. The role of technology access and experience demonstrates a fundamental limit in systems design for digital fabrication: while we can strive to expose machines and material parameters in systems and increase their level of control, there remains a question of how to provide broader access to infrastructures and tools that shape the landscape of participation in digital fabrication. It is safe to assume that the way Front's sketched chairs were made—like the products we surveyed—was nothing like compilation. Instead, how they were made had likely everything to do with access to tools, machine constraints, material properties, and process development—because these considerations also constitute the design space, not just CAD. Who gets to design and make depends on how we can integrate the full design space in future systems for digital fabrication.

ACKNOWLEDGMENTS

We'd like to thank our participants both for their work on digital fabrication and for their time given to this research. This research was supported in part by NSF Award 2007045.

REFERENCES

[1] Morgan G. Ames, Jeffrey Bardzell, Shaowen Bardzell, Silvia Lindtner, David A. Mellis, and Daniela K. Rosner. 2014. Making Cultures: Empowerment, Participation, and Democracy - or Not?. In *CHI '14 Extended Abstracts on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI EA '14)*. Association for Computing Machinery, New York, NY, USA, 1087–1092. https://doi.org/10.1145/2559206.2579405

[2] Morgan G Ames, Silvia Lindtner, Shaowen Bardzell, Jeffrey Bardzell, Lilly Nguyen, Syed Ishtiaque, Nusrat Jahan, Steven J Jackson, and Paul Dourish. 2018. Making or making do? Challenging the mythologies of making and hacking. *Journal of Peer Production* 12 (2018). http://peerproduction.net/editsuite/issues/issue-12-makerspaces-and-institutions/varia-2/making-or-making-do/.

[3] Byoungkwon An, Ye Tao, Jianzhe Gu, Tingyu Cheng, Xiang 'Anthony' Chen, Xiaoxiao Zhang, Wei Zhao, Youngwook Do, Shigeo Takahashi, Hsiang-Yun Wu, Teng Zhang, and Lining Yao. 2018. Thermorph: Democratizing 4D Printing of Self-Folding Materials and Interfaces. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173834

[4] Chris Anderson. 2014. *Makers: The New Industrial Revolution.* Crown Business.

[5] Michelle Annett. 2020. Understanding the Homepreneurship Opportunities Afforded by Social Networking and Personal Fabrication Technologies. *Proc. ACM Hum.-Comput. Interact.* 4, CSCW2, Article 99 (oct 2020), 48 pages. https://doi.org/10.1145/3415170

[6] Michelle Annett, Tovi Grossman, Daniel Wigdor, and George Fitzmaurice. 2019. Exploring and Understanding the Role of Workshop Environments in Personal Fabrication Processes. *ACM Trans. Comput.-Hum. Interact.* 26, 2, Article 10 (March 2019), 43 pages. https://doi.org/10.1145/3301420

[7] Daniel Ashbrook, Shitao Stan Guo, and Alan Lambie. 2016. Towards Augmented Fabrication: Combining Fabricated and Existing Objects. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI EA '16)*. Association for Computing Machinery, New York, NY, USA, 1510–1518. https://doi.org/10.1145/2851581.2892509

[8] Patrick Baudisch and Stefanie Mueller. 2017. Personal Fabrication. *Foundations and Trends in Human–Computer Interaction* 10, 3–4 (2017), 165–293. https://doi.org/10.1561/1100000055

[9] Patrick Baudisch, Arthur Silber, Yannis Kommana, Milan Gruner, Ludwig Wall, Kevin Reuss, Lukas Heilman, Robert Kovacs, Daniel Rechlitz, and Thijs Roumen. 2019. *Kyub: A 3D Editor for Modeling Sturdy Laser-Cut Objects.* Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300796

[10] Ian Bennink, Tim Carrigan, James Arthur, Joni Steiner, and Nick Ierodiaconou. 2013. Opendesk - Furniture designed for inspiring workplaces. https://www.opendesk.cc/, accessed Aug 2021.

[11] Paulo Blikstein and Dennis Krannich. 2013. The Makers' Movement and FabLabs in Education: Experiences, Technologies, and Research. In *Proceedings of the 12th International Conference on Interaction Design and Children* (New York, New York, USA) *(IDC '13)*. Association for Computing Machinery, New York, NY, USA, 613–616. https://doi.org/10.1145/2485760.2485884

[12] Joel Brandt, Philip J. Guo, Joel Lewenstein, and Scott R. Klemmer. 2008. Opportunistic Programming: How Rapid Ideation and Prototyping Occur in Practice. In *Proceedings of the 4th International Workshop on End-User Software Engineering* (Leipzig, Germany) *(WEUSE '08)*. Association for Computing Machinery, New York, NY, USA, 1–5. https://doi.org/10.1145/1370847.1370848

[13] Joel Brandt, Philip J. Guo, Joel Lewenstein, Scott R. Klemmer, and Mira Dontcheva. 2009. Writing Code to Prototype, Ideate, and Discover. *IEEE Software* 26, 05 (sep 2009), 18–24. https://doi.org/10.1109/MS.2009.147

[14] Amy Bruckman, Kurt Luther, and Casey Fiesler. 2015. When should we use real names in published accounts of internet research.

[15] Leah Buechley. 2014. Thinking About Making—An examination of what we mean by making (MAKEing) these days. Presented at Eyeo Festival 2014 https://vimeo.com/110616469.

[16] Amy Cheatle and Steven J. Jackson. 2015. Digital Entanglements: Craft, Computation and Collaboration in Fine Art Furniture Production. In *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing* (Vancouver, BC, Canada) *(CSCW '15)*. Association for Computing Machinery, New York, NY, USA, 958–968. https://doi.org/10.1145/2675133.2675291

[17] James Coleman, Craig Long, Andrew Manto, and Trygve Wastvedt. 2016. Lots of Parts, Lots of Formats, Lots of Headache. *XRDS* 22, 3 (apr 2016), 54–57. https://doi.org/10.1145/2893501

[18] Front Design. 2005. Materialized Sketch. https://collections.vam.ac.uk/item/O1299501/materialized-sketch-chair-front-design/, accessed Aug 2021.

[19] Front Design. 2007. Sketch Furniture by FRONT. https://www.youtube.com/watch?v=8zP1em1dg5k accessed July 2021.

[20] Audrey Desjardins and Timea Tihanyi. 2019. ListeningCups: A Case of Data Tactility and Data Stories. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA) *(DIS '19)*. Association for Computing Machinery, New York, NY, USA, 147–160. https://doi.org/10.1145/3322276.3323694

[21] Kayla DesPortes, Shiri Mund, and Clarisa James. 2021. Examining the Design and Development of a Social Justice Makerspace. *Proc. ACM Hum.-Comput. Interact.* 5, CSCW2, Article 397 (oct 2021), 26 pages. https://doi.org/10.1145/3479541

[22] Laura Devendorf, Katya Arquilla, Sandra Wirtanen, Allison Anderson, and Steven Frost. 2020. *Craftspeople as Technical Collaborators: Lessons Learned through an Experimental Weaving Residency.* Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376820

[23] Laura Devendorf, Abigail De Kosnik, Kate Mattingly, and Kimiko Ryokai. 2016. Probing the Potential of Post-Anthropocentric 3D Printing. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems* (Brisbane, QLD, Australia) *(DIS '16)*. Association for Computing Machinery, New York, NY, USA, 170–181. https://doi.org/10.1145/2901790.2901879

[24] Laura Devendorf and Kimiko Ryokai. 2015. Being the Machine: Reconfiguring Agency and Control in Hybrid Fabrication. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2477–2486. https://doi.org/10.1145/2702123.2702547

[25] Kristin N. Dew and Daniela K. Rosner. 2018. *Lessons from the Woodshop: Cultivating Design with Living Materials.* Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3174159

[26] Kristin N. Dew and Daniela K. Rosner. 2019. Designing with Waste: A Situated Inquiry into the Material Excess of Making. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA) *(DIS '19)*. Association for Computing Machinery, New York, NY, USA, 1307–1319. https://doi.org/10.1145/3322276.3322320

[27] Mustafa Doga Dogan, Patrick Baudisch, Hrvoje Benko, Michael Nebeling, Huaishu Peng, Valkyrie Savage, and Stefanie Mueller. 2022. Fabricate It or Render It? Digital Fabrication vs. Virtual Reality for Creating Objects Instantly. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI EA '22)*. Association for Computing Machinery, New York, NY, USA, Article 151, 4 pages. https://doi.org/10.1145/3491101.3516510

[28] D. Dougherty, A. Conrad, and T. O'Reilly. 2016. *Free to Make: How the Maker Movement is Changing Our Schools, Our Jobs, and Our Minds.* North Atlantic Books.

[29] Tamara Anna Efrat, Moran Mizrahi, and Amit Zoran. 2016. The Hybrid Bricolage: Bridging Parametric Design with Craft through Algorithmic Modularity. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing*

Systems (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 5984–5995. https://doi.org/10.1145/2858036.2858441

[30] Jack Forman, Mustafa Doga Dogan, Hamilton Forsythe, and Hiroshi Ishii. 2020. DefeXtiles: 3D Printing Quasi-Woven Fabric via Under-Extrusion. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '20)*. Association for Computing Machinery, New York, NY, USA, 1222–1233. https://doi.org/10.1145/3379337.3415876

[31] Frikk Fossdal, Rogardt Heldal, and Nadya Peek. 2021. Interactive Digital Fabrication Machine Control Directly Within a CAD Environment. In *Symposium on Computational Fabrication* (Virtual Event, USA) *(SCF '21)*. Association for Computing Machinery, New York, NY, USA, Article 8, 15 pages. https://doi.org/10.1145/3485114.3485120

[32] Michelle Gantt and Bonnie A. Nardi. 1992. Gardeners and Gurus: Patterns of Cooperation among CAD Users. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Monterey, California, USA) *(CHI '92)*. Association for Computing Machinery, New York, NY, USA, 107–117. https://doi.org/10.1145/142750.142767

[33] Neil Gershenfeld. 2005. *Fab: The Coming Revolution on Your Desktop–from Personal Computers to Personal Fabrication.* Basic Books.

[34] Neil Gershenfeld, Alan Gershenfeld, and Joel Cutcher-Gershenfeld. 2017. *Designing Reality: How to Survive and Thrive in the Third Digital Revolution.* Basic Books.

[35] Bruna Goveia da Rocha, Oscar Tomico, Panos Markopoulos, and Daniel Tetteroo. 2020. *Crafting Research Products through Digital Machine Embroidery.* Association for Computing Machinery, New York, NY, USA, 341–350. https://doi.org/10.1145/3357236.3395443

[36] Emrecan Gulay and Andrés Lucero. 2019. *Integrated Workflows: Generating Feedback Between Digital and Physical Realms.* Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3290605.3300290

[37] Björn Hartmann, Loren Yu, Abel Allison, Yeonsoo Yang, and Scott R. Klemmer. 2008. Design as Exploration: Creating Interface Alternatives through Parallel Authoring and Runtime Tuning. In *Proceedings of the 21st Annual ACM Symposium on User Interface Software and Technology* (Monterey, CA, USA) *(UIST '08)*. Association for Computing Machinery, New York, NY, USA, 91–100. https://doi.org/10.1145/1449715.1449732

[38] Anja Hertenberger, Barbro Scholz, Beam Contrechoc, Becky Stewart, Ebru Kurbak, Hannah Perner-Wilson, Irene Posch, Isabel Cabral, Jie Qi, Katharina Childs, Kristi Kuusk, Lynsey Calder, Marina Toeters, Marta Kisand, Martijn ten Bhömer, Maurin Donneaud, Meg Grant, Melissa Coleman, Mika Satomi, Mili Tharakan, Pauline Vierne, Sara Robertson, Sarah Taylor, and Troy Robert Nachtigall. 2014. 2013 E-Textile Swatchbook Exchange: The Importance of Sharing Physical Work. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers: Adjunct Program* (Seattle, Washington) *(ISWC '14 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 77–81. https://doi.org/10.1145/2641248.2641276

[39] Megan Hofmann, Gabriella Hann, Scott E. Hudson, and Jennifer Mankoff. 2018. *Greater than the Sum of Its PARTs: Expressing and Reusing Design Intent in 3D Models.* Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173875

[40] Nathaniel Hudson, Celena Alcock, and Parmit K. Chilana. 2016. *Understanding Newcomers to 3D Printing: Motivations, Workflows, and Barriers of Casual Makers.* Association for Computing Machinery, New York, NY, USA, 384–396. https://doi.org/10.1145/2858036.2858266

[41] Tim Ingold. 2010. The textility of making. *Cambridge Journal of Economics* 34 (2010), 91–102.

[42] Jennifer Jacobs, Sumit Gogia, Radomír Mundefinedch, and Joel R. Brandt. 2017. Supporting Expressive Procedural Art Creation through Direct Manipulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 6330–6341. https://doi.org/10.1145/3025453.3025927

[43] Jennifer Jacobs and Amit Zoran. 2015. *Hybrid Practice in the Kalahari: Design Collaboration through Digital Tools and Hunter-Gatherer Craft.* Association for Computing Machinery, New York, NY, USA, 619–628. https://doi.org/10.1145/2702123.2702362

[44] Rhys Jones, Patrick Haufe, Edward Sells, Pejman Iravani, Vik Olliver, Chris Palmer, and Adrian Bowyer. 2011. RepRap – the replicating rapid prototyper. *Robotica* 29, 1 (2011), 177–191. https://doi.org/10.1017/S026357471000069X

[45] Jonathan M. Kaldor, Doug L. James, and Steve Marschner. 2008. Simulating Knitted Cloth at the Yarn Level. In *ACM SIGGRAPH 2008 Papers* (Los Angeles, California) *(SIGGRAPH '08)*. Association for Computing Machinery, New York, NY, USA, Article 65, 9 pages. https://doi.org/10.1145/1399504.1360664

[46] Jonathan M. Kaldor, Doug L. James, and Steve Marschner. 2010. Efficient Yarn-Based Cloth with Adaptive Contact Linearization. *ACM Trans. Graph.* 29, 4, Article 105 (jul 2010), 10 pages. https://doi.org/10.1145/1778765.1778842

[47] Rubaiat Habib Kazi, Fanny Chevalier, Tovi Grossman, and George Fitzmaurice. 2014. Kitty: Sketching Dynamic and Interactive Illustrations. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology* (Honolulu, Hawaii, USA) *(UIST '14)*. Association for Computing Machinery, New York, NY, USA, 395–405. https://doi.org/10.1145/2642918.2647375

[48] Kickstarter. 2021. Kickstarter Make 100. https://www.kickstarter.com/make-100, accessed Aug 2021.

[49] Amy J. Ko, Robin Abraham, Laura Beckwith, Alan Blackwell, Margaret Burnett, Martin Erwig, Chris Scaffidi, Joseph Lawrance, Henry Lieberman, Brad Myers, Mary Beth Rosson, Gregg Rothermel, Mary Shaw, and Susan Wiedenbeck. 2011. The State of the Art in End-User Software Engineering. *ACM Comput. Surv.* 43, 3, Article 21 (apr 2011), 44 pages. https://doi.org/10.1145/1922649.1922658

[50] Amy J. Ko, Brad A. Myers, and Htet Htet Aung. 2004. Six Learning Barriers in End-User Programming Systems. In *2004 IEEE Symposium on Visual Languages - Human Centric Computing*. 199–206. https://doi.org/10.1109/VLHCC.2004.47

[51] S. Anand Kumar and R.V.S. Prasad. 2021. Chapter 2 - Basic principles of additive manufacturing: different additive manufacturing technologies. In *Additive Manufacturing*, M. Manjaiah, K. Raghavendra, N. Balashanmugam, and J. Paulo Davim (Eds.). Woodhead Publishing, 17–35. https://doi.org/10.1016/B978-0-12-822056-6.00012-6

[52] Ben Lafreniere and Tovi Grossman. 2018. Blocks-to-CAD: A Cross-Application Bridge from Minecraft to 3D Modeling. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 637–648. https://doi.org/10.1145/3242587.3242602

[53] Maria Larsson, Hironori Yoshida, Nobuyuki Umetani, and Takeo Igarashi. 2020. *Tsugite: Interactive Design and Fabrication of Wood Joints.* Association for Computing Machinery, New York, NY, USA, 317–327. https://doi.org/10.1145/3379337.3415899

[54] Manfred Lau, Akira Ohgawara, Jun Mitani, and Takeo Igarashi. 2011. Converting 3D Furniture Models to Fabricatable Parts and Connectors. *ACM Trans. Graph.* 30, 4, Article 85 (July 2011), 6 pages. https://doi.org/10.1145/2010324.1964980

[55] Amanda Lazar, Alisha Pradhan, Ben Jelen, Katie A. Siek, and Alex Leitch. 2021. Studying the Formation of an Older Adult-Led Makerspace. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 593, 11 pages. https://doi.org/10.1145/3411764.3445146

[56] Danny Leen, Nadya Peek, and Raf Ramakers. 2020. *LamiFold: Fabricating Objects with Integrated Mechanisms Using a Laser Cutter Lamination Workflow.* Association for Computing Machinery, New York, NY, USA, 304–316. https://doi.org/10.1145/3379337.3415885

[57] Danny Leen, Raf Ramakers, and Kris Luyten. 2017. StrutModeling: A Low-Fidelity Construction Kit to Iteratively Model, Test, and Adapt 3D Objects. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 471–479. https://doi.org/10.1145/3126594.3126643

[58] Danny Leen, Tom Veuskens, Kris Luyten, and Raf Ramakers. 2019. *JigFab: Computational Fabrication of Constraints to Facilitate Woodworking with Power Tools.* Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300386

[59] Jingyi Li, Sonia Hashim, and Jennifer Jacobs. 2021. What We Can Learn From Visual Artists About Software Development. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 314, 14 pages. https://doi.org/10.1145/3411764.3445682

[60] Silvia Lindtner, Shaowen Bardzell, and Jeffrey Bardzell. 2016. *Reconstituting the Utopian Vision of Making: HCI After Technosolutionism.* Association for Computing Machinery, New York, NY, USA, 1390–1402. https://doi.org/10.1145/2858036.2858506

[61] Silvia Lindtner, Garnet D. Hertz, and Paul Dourish. 2014. Emerging Sites of HCI Innovation: Hackerspaces, Hardware Startups & Incubators. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI '14)*. Association for Computing Machinery, New York, NY, USA, 439–448. https://doi.org/10.1145/2556288.2557132

[62] Jeffrey Lipton, Robert Maccurdy, Matt Boban, Nick Chartrain, Lawrence Withers Iii, Natasha Gangjee, Alex Nagai, Jeremy Cohen, Karina Sobhani, Jimmy Liu, Hana Qudsi, Jonathan Kaufman, Sima Mitra, Aldo Garcia, Anthony Mcnicoll, and Hod Lipson. 2012. FAB@HOME 3: A More Robust, Cost Effective and Accessible Open Hardware Fabrication Platform. *Proceedings of the Twenty Third Annual International Solid Freeform Fabrication Symposium, An Additive Manufacturing Conference* (2012), 125–135.

[63] Jeffrey I Lipton and Hod Lipson. 2016. 3D printing variable stiffness foams using viscous thread instability. *Scientific reports* 6, 1 (2016), 1–6.

[64] Jesse Louis-Rosenberg. 2016. Drowning in Triangle Soup: The Quest for a Better 3-D Printing File Format. *XRDS* 22, 3 (apr 2016), 58–62. https://doi.org/10.1145/2893503

[65] Cayley MacArthur, Caroline Wong, and Mark Hancock. 2019. Makers and Quilters: Investigating Opportunities for Improving Gender-Imbalanced Maker Groups. *Proc. ACM Hum.-Comput. Interact.* 3, CSCW, Article 29 (Nov. 2019), 24 pages. https://doi.org/10.1145/3359131

[66] Shiran Magrisso, Moran Mizrahi, and Amit Zoran. 2018. Digital Joinery For Hybrid Carpentry. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for

Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3173574.3173741
[67] Maryam M. Maleki, Robert F. Woodbury, and Carman Neustaedter. 2014. Liveness, Localization and Lookahead: Interaction Elements for Parametric Design. In *Proceedings of the 2014 Conference on Designing Interactive Systems* (Vancouver, BC, Canada) *(DIS '14)*. Association for Computing Machinery, New York, NY, USA, 805–814. https://doi.org/10.1145/2598510.2598554
[68] Lee Martin. 2015. The promise of the maker movement for education. *Journal of Pre-College Engineering Education Research (J-PEER)* 5, 1 (2015), 4.
[69] Janis Lena Meissner, Pradthana Jarusriboonchai, Janice McLaughlin, and Peter Wright. 2019. *More than the Sum of Makers: The Complex Dynamics of Diverse Practices at Maker Faire.* Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3290605.3300348
[70] Daniela Mitterberger, Selen Ercan Jenny, Lauren Vasey, Ena Lloret-Fritschi, Petrus Aejmelaeus-Lindström, Fabio Gramazio, and Matthias Kohler. 2022. Interactive Robotic Plastering: Augmented Interactive Design and Fabrication for On-Site Robotic Plastering. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 174, 18 pages. https://doi.org/10.1145/3491102.3501842
[71] Stefanie Mueller, Sangha Im, Serafima Gurevich, Alexander Teibrich, Lisa Pfisterer, François Guimbretière, and Patrick Baudisch. 2014. WirePrint: 3D Printed Previews for Fast Prototyping. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology* (Honolulu, Hawaii, USA) *(UIST '14)*. Association for Computing Machinery, New York, NY, USA, 273–280. https://doi.org/10.1145/2642918.2647359
[72] Vitra Design Museum, M. Kries, J. Eisenbrand, A. Bassi, W. Tegethoff, F. Ferrari, I. de Roode, C. Thau, O. Máčel, D. Sudjic, et al. 2019. *Atlas of Furniture Design.* Vitra Design Museum.
[73] David F. Noble. 1984. *Forces of production: a social history of industrial automation* (1st ed.). Knopf, New York.
[74] Charlotte Nordmoen and Andrew P. McPherson. 2022. Making Space for Material Entanglements: A Diffractive Analysis of Woodwork and the Practice of Making an Interactive System. In *Designing Interactive Systems Conference* (Virtual Event, Australia) *(DIS '22)*. Association for Computing Machinery, New York, NY, USA, 415–423. https://doi.org/10.1145/3532106.3533572
[75] Lora Oehlberg, Wesley Willett, and Wendy E. Mackay. 2015. *Patterns of Physical Design Remixing in Online Maker Communities.* Association for Computing Machinery, New York, NY, USA, 639–648. https://doi.org/10.1145/2702123.2702175
[76] Stephen Oney, Brad Myers, and Joel Brandt. 2014. InterState: A Language and Environment for Expressing Interface Behavior. In *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology* (Honolulu, Hawaii, USA) *(UIST '14)*. Association for Computing Machinery, New York, NY, USA, 263–272. https://doi.org/10.1145/2642918.2647358
[77] Huaishu Peng, Rundong Wu, Steve Marschner, and François Guimbretière. 2016. On-The-Fly Print: Incremental Printing While Modelling. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 887–896. https://doi.org/10.1145/2858036.2858106
[78] Hannah Perner-Wilson and Irene Posch. 2022. How Tangible is TEI? Exploring Swatches as a New Academic Publication Format. In *Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Daejeon, Republic of Korea) *(TEI '22)*. Association for Computing Machinery, New York, NY, USA, Article 55, 4 pages. https://doi.org/10.1145/3490149.3503668
[79] Martin Rapp, Hussam Amrouch, Yibo Lin, Bei Yu, David Z Pan, Marilyn Wolf, and Jörg Henkel. 2021. Mlcad: A survey of research in machine learning for cad keynote paper. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems* (2021).
[80] Daniela Retelny and Pamela Hinds. 2016. Embedding Intentions in Drawings: How Architects Craft and Curate Drawings to Achieve Their Goals. In *Proceedings of the 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing*. ACM, New York, NY, USA, 1310–1322. https://doi.org/10.1145/2818048.2819932
[81] David Roedl, Shaowen Bardzell, and Jeffrey Bardzell. 2015. Sustainable Making? Balancing Optimism and Criticism in HCI Discourse. *ACM Trans. Comput.-Hum. Interact.* 22, 3, Article 15 (June 2015), 27 pages. https://doi.org/10.1145/2699742
[82] Daniela K. Rosner, Miwa Ikemiya, and Tim Regan. 2015. Resisting Alignment: Code and Clay. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 181–188. https://doi.org/10.1145/2677199.2680587
[83] Greg Saul, Manfred Lau, Jun Mitani, and Takeo Igarashi. 2010. SketchChair: An All-in-One Chair Design System for End Users. In *Proceedings of the Fifth International Conference on Tangible, Embedded, and Embodied Interaction* (Funchal, Portugal) *(TEI '11)*. Association for Computing Machinery, New York, NY, USA, 73–80. https://doi.org/10.1145/1935701.1935717

[84] Valkyrie Savage, Sean Follmer, Jingyi Li, and Björn Hartmann. 2015. Makers' Marks: Physical Markup for Designing and Fabricating Functional Objects. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (Charlotte, NC, USA) *(UIST '15)*. Association for Computing Machinery, New York, NY, USA, 103–108. https://doi.org/10.1145/2807442.2807508

[85] Ryan Schmidt and Matt Ratto. 2013. Design-to-Fabricate: Maker Hardware Requires Maker Software. *IEEE Computer Graphics and Applications* 33, 6 (2013), 26–34. https://doi.org/10.1109/MCG.2013.90

[86] Ryan Schmidt and Karan Singh. 2010. Meshmixer: An Interface for Rapid Mesh Composition. In *ACM SIGGRAPH 2010 Talks* (Los Angeles, California) *(SIGGRAPH '10)*. Association for Computing Machinery, New York, NY, USA, Article 6, 1 pages. https://doi.org/10.1145/1837026.1837034

[87] D. A. Schön. 1992. Designing as reflective conversation with the materials of a design situation. *Knowledge-Based Systems* 5, 1 (1992), 3–14. https://doi.org/10.1016/0950-7051(92)90020-G

[88] Adriana Schulz, Ariel Shamir, David I. W. Levin, Pitchaya Sitthi-amorn, and Wojciech Matusik. 2014. Design and Fabrication by Example. *ACM Trans. Graph.* 33, 4, Article 62 (July 2014), 11 pages. https://doi.org/10.1145/2601097.2601127

[89] Ed Sells, Sebastien Bailard, Zach Smith, Adrian Bowyer, and Vik Olliver. 2010. *RepRap: The Replicating Rapid Prototyper: Maximizing Customizability by Breeding the Means of Production.* 568–580. https://doi.org/10.1142/9789814280280_0028

[90] Ticha Sethapakdi, Daniel Anderson, Adrian Reginald Chua Sy, and Stefanie Mueller. 2021. *Fabricaide: Fabrication-Aware Design for 2D Cutting Machines.* Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3411764.3445345

[91] Maria Shugrina, Ariel Shamir, and Wojciech Matusik. 2015. Fab Forms: Customizable Objects for Fabrication with Validity and Geometry Caching. *ACM Trans. Graph.* 34, 4, Article 100 (July 2015), 12 pages. https://doi.org/10.1145/2766994

[92] T. Smith, D.A. Sonnenfeld, and D.N. Pellow. 2006. *Challenging the Chip: Labor Rights and Environmental Justice in the Global Electronics Industry.* Temple University Press. https://books.google.co.ug/books?id=Rpq1AAAAIAAJ

[93] N. Stephenson. 2011. *The Diamond Age.* Penguin.

[94] Blair Subbaraman and Nadya Peek. 2022. P5.Fab: Direct Control of Digital Fabrication Machines from a Creative Coding Environment. In *Designing Interactive Systems Conference* (Virtual Event, Australia) *(DIS '22)*. Association for Computing Machinery, New York, NY, USA, 1148–1161. https://doi.org/10.1145/3532106.3533496

[95] Haruki Takahashi and Jeeeun Kim. 2019. 3D Printed Fabric: Techniques for Design and 3D Weaving Programmable Textiles. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology* (New Orleans, LA, USA) *(UIST '19)*. Association for Computing Machinery, New York, NY, USA, 43–51. https://doi.org/10.1145/3332165.3347896

[96] Cesar Torres and Eric Paulos. 2015. MetaMorphe: Designing Expressive 3D Models for Digital Fabrication. In *Proceedings of the 2015 ACM SIGCHI Conference on Creativity and Cognition* (Glasgow, United Kingdom) *(C&C '15)*. Association for Computing Machinery, New York, NY, USA, 73–82. https://doi.org/10.1145/2757226.2757235

[97] Hannah Twigg-Smith, Jasper Tran O'Leary, and Nadya Peek. 2021. Tools, Tricks, and Hacks: Exploring Novel Digital Fabrication Workflows on #PlotterTwitter. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 594, 15 pages. https://doi.org/10.1145/3411764.3445653

[98] Ron Wakkary, Henry Lin, Shannon Mortimer, Lauren Low, Audrey Desjardins, Keith Doyle, and Philip Robbins. 2016. Productive Frictions: Moving from Digital to Material Prototyping and Low-Volume Production for Design Research. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems* (Brisbane, QLD, Australia) *(DIS '16)*. Association for Computing Machinery, New York, NY, USA, 1258–1269. https://doi.org/10.1145/2901790.2901880

[99] Christian Weichel, Manfred Lau, David Kim, Nicolas Villar, and Hans W. Gellersen. 2014. MixFab: A Mixed-Reality Environment for Personal Fabrication. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI '14)*. Association for Computing Machinery, New York, NY, USA, 3855–3864. https://doi.org/10.1145/2556288.2557090

[100] Tara Whelan. 2018. We Are Not All Makers: The Paradox of Plurality In The Maker Movement. In *Proceedings of the 2018 ACM Conference Companion Publication on Designing Interactive Systems* (Hong Kong, China) *(DIS '18 Companion)*. Association for Computing Machinery, New York, NY, USA, 75–80. https://doi.org/10.1145/3197391.3205415

[101] Matt Woodward. 2005. Make magazine: premier issue. https://arstechnica.com/features/2005/03/make-magazine/

[102] Jiaxian Yao, Danny M. Kaufman, Yotam Gingold, and Maneesh Agrawala. 2017. Interactive Design and Stability Analysis of Decorative Joinery for Furniture. *ACM Trans. Graph.* 36, 2, Article 20 (March 2017), 16 pages. https://doi.org/10.1145/3054740

[103] Nur Yildirim, James McCann, and John Zimmerman. 2020. *Digital Fabrication Tools at Work: Probing Professionals' Current Needs and Desired Futures.* Association for Computing Machinery, New York, NY, USA, 1–13. https:

//doi.org/10.1145/3313831.3376621
[104] Cem Yuksel, Jonathan M. Kaldor, Doug L. James, and Steve Marschner. 2012. Stitch Meshes for Modeling Knitted Clothing with Yarn-Level Detail. *ACM Trans. Graph.* 31, 4, Article 37 (jul 2012), 12 pages. https://doi.org/10.1145/2185520.2185533
[105] Malgorzata A Zboinska and Delia Dumitrescu. 2020. On the Aesthetic Significance of Imprecision in Computational Design: Exploring Expressive Features of Imprecision in Four Digital Fabrication Approaches. *International Journal of Architectural Computing* (2020), 1478077120976493.
[106] Shuang Zhao, Wenzel Jakob, Steve Marschner, and Kavita Bala. 2012. Structure-Aware Synthesis for Predictive Woven Fabric Appearance. *ACM Trans. Graph.* 31, 4, Article 75 (jul 2012), 10 pages. https://doi.org/10.1145/2185520.2185571
[107] Amit Zoran and Leah Buechley. 2013. Hybrid reassemblage: an exploration of craft, digital fabrication and artifact uniqueness. *Leonardo* 46, 1 (2013), 4–10.
[108] Shoshana Zuboff. 1988. *In The Age Of The Smart Machine: The Future Of Work And Power.* Heinemann Professional.

A PARTICIPANT BIOGRAPHIES

A.1 Che-Wei Wang - Dropped Pendant Light

Che-Wei Wang is an artist, designer & architect with expertise in computational and generative design, fabrication technologies, electronics, CNC machining, and metal manufacturing. The results range from architecture and sculpture to interactive installations & mobile apps. He is the winner of the 2003 SOM fellowship and the Young Alumni Achievement Award from Pratt Institute. Che-Wei has taught courses on design, time, creative computing, and inflatables, at various institutions. He is an alumnus of MIT Media Lab, ITP at NYU, and Pratt Institute.

A.2 Taylor Levy - Dropped Pendant Light

Taylor Levy is an artist & designer with a penchant for taking things apart, understanding how they work, and then putting them back together in a way that exposes their inner workings. The results take on a variety of forms from low-tech electronic sculpture to high-tech software and other executions. She has work on view at The Leonardo Museum of Science and Technology and was a resident at Fabrica Interactive in Treviso, Italy. She is an alumna of MIT Media Lab, ITP at NYU, and Vassar College. Both Taylor and Che-Wei are recipients of the 2022 Cooper Hewitt National Design Award for Product Design.

A.3 Timea Tihanyi - Listening Cups

Timea Tihanyi is a Hungarian-born interdisciplinary visual artist and ceramicist living and working in Seattle, Washington. Tihanyi holds a Doctor of Medicine degree from Semmelweis University, Budapest, Hungary; a BFA in Ceramics from the Massachusetts College of Art in Boston; and an MFA in ceramics from the University of Washington.

Tihanyi's work has been exhibited in the United States, Brazil, Australia, Denmark, Spain and the Netherlands, including Shepparton Art Museum, Henry Art Gallery, Bellevue Art Museum, Mint Museum of Art and Design, Society for Contemporary Craft in Pittsburg, Clay Center for the Arts and Sciences, Foundry Art Center, International Museum of Surgical Science, SculptureSpace NYC and the Museum of Glass, Tacoma. She has received many recognitions, including the 2018 Neddy Award in Open Media, a 2018-19 Bergstrom Award, and a New Foundation travel grant. In Seattle, her work has been part of numerous solo and group exhibitions at Gallery 4Culture, CoCA, Consolidated works, Seattle Art Museum (SAM) Gallery, Davidson Contemporary, and SOIL Gallery. Her 3D printed sculptural ceramic work was represented by Linda Hodges Gallery at the time of the interview, while she also sells Slip Rabbit pieces through various other venues.

Tihanyi is a Teaching Professor in the Interdisciplinary Visual Arts program at the University of Washington. She is the founder and director of Slip Rabbit, a unique mentoring space for experimentation and learning at the intersections of art, design, architecture, science and engineering. Slip Rabbit is the first technoceramics studio in the Pacific Northwest.

A.4 Audrey Desjardins - Listening Cups

Audrey Desjardins is an associate professor in interaction design at University of Washington, in the School of Art + Art History + Design, and adjunct associate professor in Human Centered Design and Engineering and in Digital Arts and Experimental Media . She holds a PhD and Master of Arts from the School of Interactive Arts + Technology at Simon Fraser University. Prior to that, she studied industrial design at Université de Montreal.

Using a critical lens, her research investigates experiences of living with technology in the home. She use methods like research-through-design, autobiographical design, and participatory design as approaches to critique and reimagine current visions of Internet of Things technologies.

She is the director of Studio Tilt, a design research studio that questions and considers familiar encounters between humans and things.

A.5 Antoine Fritsch - CORAIL Table

Trained as a designer, with a strong technological background, Antoine Fritsch has been leading the Fritsch-Durisotti Agency since he co-founded it in 1993. He ensures the direction of design and particularly oversees the balance of an activity shared between complex industrial creation projects and “Free Expression” projects that have been punctuating the path of the agency from its beginnings.

A.6 Victor De Bono - CORAIL Table

De Bono is an engineer–architect graduated from the Institut National des Sciences Appliquées (INSA) of Lyon and the Ecole Nationale Supérieure d’Architecture (ENSA) of Lyon, Victor develops urban, landscape and maritime projects, as well as new certified constructive systems integrating 3D printing.

A.7 Jessica Rosenkrantz - Coral Cup

Jessica Rosenkrantz is an artist, designer, and programmer. She graduated from MIT with degrees in biology and architecture in 2005. And studied architecture at the Harvard Graduate School of Design from 2005 to 2008 before leaving to found Nervous System. She was a Lecturer at MIT from 2016 to 2019 teaching design.

A.8 Jesse Louis-Rosenberg - Coral Cup

Jesse Louis-Rosenberg is an artist, computer programmer, and maker. Jesse is interested in how simulation techniques can be used in the design and in the creation of new kinds of fabrication machines. He studied math at MIT and previously worked at Gehry Technologies in building modeling and design automation. With Jessica, Jesse is the co-founder of Nervous System. The work of Nervous System has been published in the journal Science, acquired by the Museum of Modern Art, and featured in major press venues including the New York Times.

A.9 Matt Hutchinson - Other Vessels

Matt Hutchinson is an architect, educator, and experienced fabricator interested in exploring the potential convergence of traditional and digital fabrication processes within architecture. He draws from a diverse range of professional experiences to inform the multi-disciplinary and collaborative approach for his own design practice, PATH. Matt earned his Bachelor of Architecture at Kent State University and his Master of Architecture at Yale University, where he received the Eero Saarinen scholarship and was twice a finalist for the H. I. Feldman design prize, the school’s highest design honor. He recently taught a series of advanced architecture studios and material and fabrication seminars at the California College of the Arts and has been a fellow at Autodesk’s Pier 9 Residency.

A.10 Oliver David Krieg - AESTUS

Oliver David Krieg is an expert in computational design and digital fabrication in architecture. As Chief Technology Officer (CTO) at Intelligent City in Vancouver, Canada, he is leading the technology development for computational design and digital manufacturing processes for a proprietary high-rise mass timber construction system. This is part of the company’s effort to provide transformative solutions for platform-based, sustainable and affordable urban housing. His work is characterized by an integrative approach towards engineering, material science, sustainability, and manufacturing. He received his PhD from the Institute for Computational Design and Construction at the University of Stuttgart, Germany. His work aims to enable reciprocities between design, technology and materiality in order to re-conceptualize how architecture can be designed, fabricated, and constructed.

A.11 Anne Filson - AtFAB

Anne Filson is an architect and the Sue Fan Gooding and Lyde Gooding Endowed Professor at the University of Kentucky. She teaches the Commonwealth Studio and Research Seminar, as well as courses on entrepreneurship and new models of architectural practice. She is a co-founder of the architecture, design, and research firm Filson and Rohrbacher.

A co-author of Make: Design for CNC, Filson writes and speaks internationally on design, maker culture, entrepreneurship, and the social and economic potentials of networked, local manufacturing. Filson is a co-PI of the Atomic Cities Research Group, which to date has received over $1M in funding from the US Department of Energy.

Filson worked as a Project Architect for Rem Koolhaas' Office for Metropolitan Architecture and as a Design Strategist for IDEO's Smart Space practice. She's a LEED Accredited Professional and NCARB Certified, Registered Architect. She earned her Master of Architecture from Columbia University, and Bachelors of Arts in Art History from Smith College.

A.12 Dena Molnar - WOVNS

Dena Molnar is the Vice President of Design at Luna Textiles. She has a background in design and fabrication of textiles for interiors. Prior to completing an MDes in technology at the Harvard graduate school of design, she earned a BFA in textiles from Rhode Island School of Design, and went on to design for leading manufacturers and suppliers of textiles to commercial architects and designers in New York City. She has over 13 years of industry experience, including time spent as a textile technology consultant to Google, a consultant for MIT, a senior designer at Maharam textiles, and cofounder of WOVNS.

A.13 Brooks Hagan - Weft Create

Brooks Hagan is a textile designer, artist and researcher. He designs for various textile companies and consults with industry partners such as Apple, Inc. and Under Armour. A recent project with computer scientists at Cornell and Stanford Universities investigates advanced visualization for the design of constructed textiles and is funded by a $1.2M grant from the National Science Foundation (NSF). In 2015 Hagan cofounded the textile technology company Computational Textiles Inc, which was awarded NSF SBIR support to catalyze private sector commercialization of the most promising technological innovations. Computational Textiles launched its first software platform, Weft, in 2017. Hagan's research with the Virtual Textile Research Group investigates historical industrial textile processes, advanced manufacturing processes, volumetric weaving for rapid prototyping and new computational tools for textile design. Hagan collaborates with many fine artists and works with the Dieu Donne Papermill in New York to explore paper materials and textiles. He is interim dean and professor at Rhode Island School of Design (RISD) and has previously served as graduate program director and head of RISD's textile department.

Product	*Participants*	*Affiliations*	*Education*	*Resources*
Dropped Pendant Light	Che-Wei Wang, Taylor Levy	CW&T	architecture, computer science, film	home fabrication shop
Listening Cups	Timea Tihanyi, Audrey Desjardins	Slip Rabbit	ceramics, visual arts, digital craft, industrial design, interaction design	techno-ceramics research studio
CORAIL Table	Antoine Fritsch, Victor De Bono	Fritsch + Durisotti, XTree	industrial design, architecture, materials science, robotics	design and prototyping studio, proprietary 3D printing and robot arm
Coral Cup	Jessica Rosenkrantz, Jesse Louis-Rosenberg	Nervous System	architecture, biology, computer science, math	fabrication shop and design studio
Other Vessels	Matt Hutchinson	Path Design	architecture, traditional fabrication	personal studio with small tools, access to industrial CNC equipment through affiliation with Autodesk, partnership with glassblowing facility
AESTUS	David Krieg	ODK Design	architecture, computational design, digital fabrication	collaboration with 3rd party robotic fabrication facility
AtFAB	Anne Filson	Filson and Rohrbacher	architecture design	affiliation with 3rd party fabrication facility
WOVNS	Dena Molnar	WOVNS	textile design, weaving	affiliation with industrial textile mill with experience in on-demand services
Weft Create	Brooks Hagan	Weft	industrial textile production, product design, marketing	affiliation with industrial textile mill

Table 1. Overview of participants' background, affiliations, and available resources.

Product	*Software*	*Materials*	*Equipment*
Dropped Pendant Light	Fusion 360, Rhino + Grasshopper	PLA, LED bulb and socket	consumer-grade FDM 3D printer
Listening Cups	Rhino, Microsoft Excel, Decibel X	ceramics	porcelain 3D printer, ceramic kiln
CORAIL Table	Rhino + Grasshopper, Fusion 360, custom software	concrete, glass, and steel	proprietary 3D printing head (developed by the company), robotic arm
Coral Cup	custom design software, Rhino, Processing, Blender, Adobe Photoshop	porcelain, glaze, plaster, silicone rubber, SLA 3D printer resin	SLA 3D printer, ceramic kiln, vibrating table
Other Vessels	Rhino + Grasshopper, Fusion 360	glass, aluminum, PLA	CNC mill, 3D printer, glassblowing equipment
AESTUS	Grasshopper, custom CNC software	beech plywood, steel, felt	industrial robot with mounted carving tool
AtFAB	Processing, Fusion 360, Form-Z, SketchUp	plywood	CNC mill
WOVNS	custom software	textiles	industrial textile mill
Weft Create	custom software	textiles	industrial textile mill

Table 2. Overview of tools and materials used in each production workflow.