Understanding Newcomers to 3D Printing: Motivations, Workflows, and Barriers of Casual Makers

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ABSTRACT
Interest in understanding and facilitating 3D digital fabrication is growing in the HCI research community. However, most of our insights about end-user interaction with fabrication are currently based on interactions of professional users, makers, and technology enthusiasts. We present a study of *casual makers,* users who have no prior experience with fabrication and mainly explore walk-up-and-use 3D printing services at public print centers, such as libraries, universities, and schools. We carried out 32 interviews with casual makers, print center operators, and fabrication experts to understand the motivations, workflows, and barriers in appropriating 3D printing technologies. Our results suggest that casual makers are deeply dependent on print center operators throughout the process—from bootstrapping their 3D printing workflow, to seeking help and troubleshooting, to verifying their outputs. However, print center operators are usually not trained domain experts in fabrication and cannot always address the nuanced needs of casual makers. We discuss implications for optimizing 3D design tools and interactions that can better facilitate casual makers' workflows.

Author Keywords
3D printing; casual makers; 3D modelling; learning barriers.

ACM Classification Keywords
H.5.2. Information interfaces and presentation (*e.g.*, HCI): User Interfaces: Prototyping.

INTRODUCTION
The declining cost of fabrication hardware over the last few years has catalyzed the design of 'prosumer' machines and created new opportunities for consumers to make, create, and innovate [31]. This has led to the emergence of *makers*, a community of enthusiasts who focus on fabrication, invention and experience sharing, and who collaborate and learn in environments known as *makerspaces* [16]. Inspired by the makerspace concept, thousands of public institutions, such as schools [33], libraries [53], and universities [14,55], are now setting up print centers or creative hubs for end users to make use of digital fabrication technologies. However, unlike makerspaces that are often run by enthusiasts and have formal memberships that attract engineers, entrepreneurs, inventors, hackers, craftsmen, and artists [29,39,46,52], public print centers welcome users of all ages and skill levels [3] and offer 3D printing services for free or at nominal rates.

In our research, we use the term *casual makers* to describe users who have no prior experience with fabrication and mainly explore 3D printing at public print centers. Although focus on makers and enthusiasts [3,29,48], and professional users [23,24,43,57] is growing in human-computer interaction (HCI), we are only beginning to understand the emerging population of casual makers. This population is particularly interesting to study because casual makers can serve as a proxy for what it will be like for the general public to use 3D printing once this technology becomes even more economical and ubiquitous. We argue that if HCI is going to be at the forefront of inventing new fabrication design tools and interfaces [28], we need to look beyond enthusiasts and understand the challenges and opportunities that exist in facilitating the interactions of casual makers with fabrication technology.

In this paper, we investigate how casual makers explore the world of walk-up-and-use 3D printing services, focusing on their motivations, workflows, and barriers. We carried out semi-structured interviews with users who had little or no prior fabrication or 3D modelling experience, but had recently visited a print center to try out 3D printing. To understand the full spectrum of casual making, we also solicited perspectives of *print center operators* and experts in fabrication. Based on findings from 32 interviews, we provide a comprehensive analysis of what it is like for casual makers to interact with complex 3D printing workflows at public print centers, the role of operators, and how casual makers' interactions differ from fabrication experts.

Our main findings indicate that there is a strong interdependency between the different stages of a casual maker's fabrication workflow (Figure 1) that impacts the whole user experience. We further found that casual makers often struggle in every part of this workflow, from creating their 3D model to forming a mental model for 3D geometry to creating their final printed outputs. Although some of our participants avoided the difficulty of learning 3D modelling by

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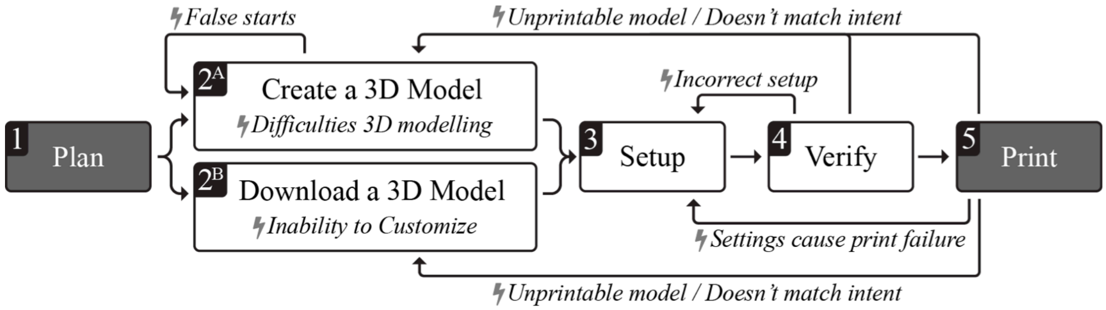

Figure 1: A casual maker passes through several steps when attempting to 3D model and print, and may have to return to earlier steps in response to some errors. Different parts of the workflow are associated with different user challenges.

turning to premade 3D models available through services such as *Thingiverse.com*, they were often deterred by the limited options to customize the models. We found that casual makers were successful only with the help of print center operators at every stage—from bootstrapping their 3D printing workflow, to seeking help and troubleshooting, to verifying their outputs. However, the operators could not always address the nuanced needs of casual makers as the operators were not formally trained in fabrication.

There are two key implications of our findings that we reflect on in our discussion: 1) current tools that focus on supporting only one aspect of the workflow (*e.g.*, only modelling or only printing) may be less useful for casual makers and there is opportunity in HCI research to innovate on design tools that take into account the interdependencies within the 3D printing workflow; and 2) while lowering the usability barriers of fabrication tools is important, it is perhaps even more important to weave-in expertise on best practices and troubleshooting tips within the walk-up-and-use tools used by casual makers to reduce their dependency on operators.

Our paper makes the following main contributions:

- Establishes an empirical understanding of casual makers' motivations, workflows and barriers in using 3D printing technologies and illustrates the role of print center operators in providing support throughout the process.
- Provides insights into public print centers and how they lower the barrier to access for 3D printing technologies, but currently lack the kind of community expertise and knowledge sharing that is the hallmark of makerspaces.
- Highlights the opportunities that exist in building the next generation of inter-connected fabrication tools with features for supporting expertise sharing.

RELATED WORK

Since 3D design and fabrication tools have traditionally targeted professionals or technically inclined users, much of the extant HCI literature focuses on experts. However, research on facilitating consumer end user interaction with digital fabrication and making has recently been growing [28]. To situate our findings, we draw upon research related to makers and makerspaces, observational studies of 3D printing in other contexts, and pedagogical experiences.

Makers and Makerspaces

Recent years have seen the emergence of *makerspaces*, community organizations where enthusiasts, known as *makers*, brainstorm, build, and share their work [29,52]. Typically run by enthusiasts and makers [9,39,52], these spaces attract technically literate users who often have formal engineering, science or design training. Makerspaces provide a number of benefits to their members. In exchange for a membership fee (usually a commitment of $50 to $100 monthly [3]) makers gain access to a space outfitted for creative work and a wide range of tools from humble handsaws up to 3D printers and other digital fabrication tools. More importantly, however, makers become part of an informal network of expertise sharing [3,29,52] and undertake projects that they would otherwise be unable to do on their own [29,46,52]. All of this creates a strong sense of community among the members of the makerspace. However, our study shows that print centers do not offer this type of expertise sharing—they are run by operators who usually do not have any formal training in 3D printing and are mainly there as facilitators.

Other works have considered the culture of these makers [16,21,31]. These studies describe a culture of customization, collaboration and knowledge sharing by technically inclined users who may or may not have formal training in 3D workflows but are intrinsically motivated by the process of learning new skills. This drive to tinker separates these enthusiasts from the casual makers that we examined in our study.

3D Printing and Modelling Behaviors in Other Contexts

Much of the work examining user interactions and experiences around 3D printing and modelling has focused on technical or professional users. For example, Lee et al. [23] evaluated the usability of ten different professional 3D software packages and highlighted issues related to confusing terminology, form design, help systems, and more. Sadar and Chyon [43] and Ludwig et al. [25] document experiences of professionals using 3D printing in research and artistic contexts respectively, showing how they experimented to learn how printer settings influenced output. Mellis and Buechley [27] document a case study of fabrication of customized electronic products through workshops with trained users which employed 3D printing. In these workshops they found the limited time they had available made it difficult for these users to produce finished 3D prints. While these papers document a range of usability issues, they have primarily considered enthusiasts and professional users—that is, they were trained or technically literate in fabrication. In contrast, as we demonstrate in the paper, casual makers may have different needs and motivations, cannot draw upon formal technical training, and face additional usability issues.

Shewbridge et al. [47] consider users who most closely match our definition of casual makers. They investigated the types of objects that users would wish to create in a typical household equipped with a 3D printer. However, the authors used an idealized form of a 3D printer capable of creating anything, and requiring no technical knowledge or time investment on the part of the user. While they found interest in a wide variety of objects including modifications and customizations of existing designs, their study was not concerned with the entirety of the complex 3D modelling and printing workflows that was the focus of our study.

Finally, recent studies are looking at the online 3D model sharing culture emerging in websites such as *Thingiverse*. For example, large-scale analyses of Thingiverse 3D models have shed light on how users modify each other's designs, with a focus on network structures [22,34,36], the sharing of assistive devices [5], and license choices [30]. Although model sharing was a topic of discussion in our interviews, sharing culture was not the focus of this study. However, we do add insights about limitations of using shared 3D models in casual makers' workflows.

Teaching and Pedagogical Experiences in 3D Printing

3D printing and modelling is also receiving increased attention in the education space, with studies documenting experiences implementing and teaching 3D printing in academic environments. Some have explored the educational potential of making in a formal learning environment [4,11,55], finding that it provided students with hands-on experience and increased student motivation, performance and information retention. Additionally, Buehler et al. [6] studied the use of 3D printing and modelling in special education classrooms, and found that even with novice-oriented tools such as *TinkerCAD*, students struggled to create their own designs. Our results corroborate these findings in a non-formal context, and shed light on further challenges faced in other parts of the 3D printing workflow.

Several case studies have investigated experiences installing 3D printers in public and university libraries [13,14,41,44]. These cases provide some insight into how these print centers were set up, but do not provide detailed insights into the workflows and barriers of casual makers independently trying to fabricate digital objects using the tools provided by these print centers.

In summary, although literature on various aspects of makers, 3D modelling and digital fabrication is growing in HCI, to our knowledge our study is among the first to investigate casual makers and their use of walk-up-and-use 3D print centers.

METHOD

Research Approach

To establish an empirical understanding of the needs, workflows, and barriers faced by casual makers, we carried out 32 semi-structured interviews[1]. Our interviews were inspired by seminal works on understanding and illustrating the complexity of user interaction with machines [37,50]. Although our primary target audience was casual makers, we also considered the perspectives of print center operators (as they interacted with these casual makers every day) and fabrication experts (to compare our findings about casual maker workflows).

Recruitment and Participants

Most of our data and analysis is based on interviews with 18 adult casual makers (11 male, 7 female) from our local metropolitan area. These casual maker participants varied in age: 33% were between 18-24, 29% were 25-34, 21% were 35-49, and 17% were 50-64. All of the participants had been using computers for at least 10 years, but only one had extensive experience with programming. Half of the participants had no experience with 2D graphic design software (*e.g.*, *Photoshop*), 3 had formal training in graphic design, while the others fell somewhere in-between. We recruited participants who did not have any prior 3D modelling experience or formal training and had recently visited a print center to explore 3D printing. They had explored 3D printing out of interests in areas such as robotics, kinesiology, games, and arts, with varying degrees of success.

We also recruited print center operators for our study as they interacted with casual makers every day and could share observations of these users' workflows and potential struggles as they tried out 3D modelling and printing. The operators in our study were all paid staff or volunteers who managed the operations of public print centers and came from backgrounds such as library science, education and IT. None of them had formal domain expertise in 3D modelling and were not self-identified makers. We interviewed 9 operators at 5 different local print centers, including our own university, public libraries, and schools. We interviewed 5 of the print center operators on site as that helped us capture an understanding of the resources available and the processes in place at these locations.

To compare our findings about casual makers, we also wanted to have perspectives of fabrication experts. We interviewed 5 expert users of 3D printing and modelling, who self-identified as makers or had formal education in 3D modelling (*e.g.*, industrial design, architectural design).

We recruited participants using personal contacts, email advertisements, and snowball sampling over a period of 6 months in 2015. Each of the interviews lasted 30-45 minutes.

[1] Quotes with casual makers in this text are attributed to P1-P18, quotes with operators to O1-O9, and quotes with experts to E1-E5

	Makerspaces	Print Centers
Culture	Strong, emphasis on sharing	Weak, no emphasis on sharing
Tools available	Many, often including loud or dangerous tools like table saws	Few, typically restricted to quiet and clean tools
Troubleshooting	Peer-to-peer and informal expertise sharing	Hierarchical, with users deferring to operators
Fees	Typically $50-100 monthly	Free or low cost, based on usage
Run by	Enthusiasts	Library or school staff
Technical literacy of users	High, often formally trained	Various
User commitment	High	Low

Table 1: Comparison of Makerspaces and Print Centers.

Data Collection

During the interviews with casual makers, we asked questions about what motivated the participants to begin learning 3D tools, what their first experiences had been like, their typical workflow, and the kinds of challenges that the participants faced along the way. In our interview with operators, we inquired about the operator's role, experience and training, and their perception of casual makers' experiences, as well as resources (such as materials for learning 3D modelling) and processes instituted by the print center (such as print approval). We encouraged both groups to describe how casual makers sought help and resolved issues, and to provide specific examples whenever possible. Finally, we talked to fabrication experts about their "ideal" 3D printing workflows so we could compare our findings about casual makers.

Data Analysis

All transcripts were organized, coded, and analyzed using the *Atlas.ti* data analysis software. To understand different facets of our data, we used an inductive analysis approach [49]. In the coding process, we focused on highlighting different aspects of the casual makers' workflows, the kinds of challenges that they faced, and how they attempted to resolve these challenges.

PRINT CENTERS AND THEIR OPERATORS

To understand casual makers' workflows, we first wanted to better understand the print centers where casual makers were accessing 3D printing technologies. Through our field visits, we found that these print centers were recent endeavors (less than 2 years old), equipped with *fused deposition modelling*[2] (FDM) type 3D printers. Among the print centers that we visited, three of them were using two *Makerbot Replicator 2* printers, which are single nozzle FDM printers. These two locations charged a nominal fee based on the time taken for an object to print, and offered mandatory training classes covering how to set up and use the printer before a user could use the printer. Another center was using a single newer version of the same printer, a *Makerbot Replicator 5th Gen.*, which is also a single nozzle FDM printer, and provided it for free along with optional training classes. All of these locations used the *Makerbot Desktop* slicer. The remaining location employed a single high-end *Stratasys Fortus 360mc* printer, which is a dual-nozzle enclosed FDM printer along with the associated *Insight* slicing software, and charged at-cost by material use.

According to the operators, these print centers presented benefits not found in the original makerspaces (Table 1). For example, although local makerspaces offered a few hours weekly for free community access, they were not generally accessible without paying the membership fee, which turned away newcomers to 3D printing. However, print centers had a low barrier to entry as they usually had no formal membership or membership fees, allowing less committed users to easily access the tools. Casual makers also commented that the presence of enthusiasts and experts in makerspaces often intimidated the casual makers who had no prior fabrication experience and considered themselves to be "outsiders".

The operators in our sample filled many roles: providing 1-on-1 or group training, approving user designs for printing, assisting users to find help resources, troubleshooting printers, managing user frustrations, managing other tools at the print centers, and more. All of them had learned on the job or through tutorials, but had no formal training in 3D modelling and printing. As such, these operators did not see themselves as experts (compared to makers), nor did they know the particulars of the various technicalities and advanced features of the 3D modelling and printing software. However, operators were able to defer to other experts in their networks with more expertise to address users' issues. These more experienced people were local enthusiasts, software or hardware vendors, or other more experienced operators, as described by one of our operators, a librarian by training:

> *When we launched this service, none of us knew anything about 3D printing - we just knew it was cool. In terms of training, then, we brought in someone from a local Makerspace… day one he opened the [3D Printer] with us and did some training with us and then he went away. Staff got to practice for a week and then [he] came back just to make sure everything was okay. (O6)*

We found that operators deferred to experts for specific software problems, malfunctioning or broken equipment, particularly problematic prints, or other instances where a user or operator was unable to resolve the issue.

CASUAL MAKERS AND THEIR WORKFLOWS

We now describe the focus of our study—characteristics of casual makers and their motivations, workflows, and challenges in using 3D printing technologies.

[2] *Fused deposition modelling* describes a common and relatively inexpensive 3D printing process whereby melted plastic is deposited layer by layer to form a 3D object.

Casual Makers’ Motivations for Using 3D Printing

The casual makers in our sample demonstrated several distinctive qualities. For example, unlike makers and enthusiasts, who often find learning new technologies and tools to be intrinsically motivating [10,42], we observed that casual makers were more driven by the printing output. The casual makers were motivated to produce their desired objects, whether those objects were practical or novel in nature. For most casual makers, 3D printing was merely a means-to-an-end. We observed that they often became involved with 3D printing to accomplish a specific fabrication goal. For example, one participant with a physiotherapy background wanted to prototype a new therapeutic device he had designed:

> *At first, I didn't know about 3D printing. It's just, like, "Okay, how can I make a plastic model?". You know those molds and pouring stuff in. I first thought about that, and then..."Aw, man, this is ridiculous." I don't even know what my design looks like. It's tough… It was an article that I read that I heard about 3D printing. That's when I was like, “Whoa! That's the answer! I've got to do 3D printing!” (P6)*

Other casual makers reported printing a variety of practical and emotionally appealing objects. For example, they described projects, such as 3D text, simple jewelry and cell phone cases, along with objects, such as missing board game pieces and pill bottle holders (Figure 2):

> *I needed [better] medicine containers. My father has daily medicines, so we have these little cups and they always get knocked over. I 3D printed almost like a holder for it. So they're a little bit more stable. I took the thing, I measured it and I modeled it up and printed it in different colors…(P4)*

As their use of 3D printing was not part of a long-term desire to print 3D objects, these casual makers were not yet ready to buy their own home printers and preferred to use free or low cost public access printer (such as the libraries we visited). Use of shared printers allowed casual makers to avoid both the financial cost of buying the printer, as well as the learning and time burden that comes with selecting, setting up and then maintaining the printer:

> *I think that if you're an engineer and you're interested in the technology itself or investigating what you can do with new materials or new speeds or new apparatuses then by all means get the printer. But I don't care, I want it to be a black box that's just a service… I'd much rather let somebody else [own the printer], someone whose full time job it is to maintain this device. (P2)*

Table 2 summarizes the types of projects that the casual makers in our study described, illustrating that they were usually driven by a specific practical need.

Casual Makers’ 3D Printing Workflows

Based on casual makers’ own descriptions and operators’ observations, we synthesized a 5-step model for a typical casual maker’s workflow with 3D printing (Figure 1).

Step 1: Plan the 3D Object

Before beginning the modelling or printing process, a user must first have an idea of what they want to create. We did not observe significant difficulties in idea generation, with casual makers attempting a wide range of projects, as discussed above. However, we did observe that whereas fabrication experts invested heavily in planning by using paper-based sketching and other techniques, casual makers jumped into creating their digital model with only minimal planning.

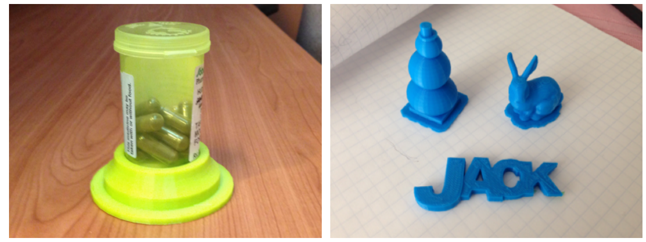

Figure 2: 3D printed objects seen in our interviews.

Type	Users (/18)	Example Project
Artistic	8	Design and fabrication of new kinetic art installation
Novelties	6	Small figurines and toys not part of any larger theme
Personalized Gifts	5	Custom novelty rings and decor for a bridal shower
Utilities	5	Pill bottle organization system
Hobbies	4	Parts for small model racing cars
Academic	4	Test for just noticeable difference in size for psychology experiment
Entrepreneurial	3	Design of a new prosthetic

Table 2: Types of projects casual makers created.

Step 2A: Create a 3D Model

Next, whereas fabrication experts would choose a modelling tool from their repertoire that was most suitable for the modelling task, casual makers tended to consistently use a single tool for all kinds of models. Casual makers either used software already installed on print center computers or opted to install modelling software on their own computers. Casual makers used and attempted a wide variety of software, with 33 different 3D tools being mentioned across our 18 casual maker interviews. Popular tools included *SketchUp* (attempted by 44% of participants), *123D Design* (22%), *openSCAD* (17%), *Solidworks* (17%) *and Blender* (11%).

Step 2B: Download a 3D Model

As an alternative to creating their own 3D model, users could download a premade 3D model from a website such as Thingiverse. Thingiverse is a platform for sharing user-contributed 3D models designed for 3D printing. On this site, members upload 3D model files (typically STL files[3]), which can then be downloaded by users of the site. We found this to be popular among users who were frustrated by the difficulty of using 3D modelling software, and was mentioned by the

[3] The STL file format is a format commonly used for 3D printing, and describes a 3D surface built up of triangles. STL files are typically not used natively by 3D software, but are generated to be shared online or processed by the 3D printer [12].

participants in 11 of the 18 casual maker interviews, and in all operator interviews.

Step 3: Set up the Printer

The next step after creating or downloading a digital model was to prepare it for printing. With help from operators, participants would set up their 3D prints by processing their 3D model into instructions for the printer and physically preparing the printer. Processing the 3D model occurred in specialized software known as a *slicer* (as it slices the model into layers for the printer), which allowed users to select print settings, such as layer height and print speed.

Step 4: Verify the Model

In the print centers that we visited, operators sometimes checked the user's digital model via an onscreen inspection before printing. This check was designed to evaluate whether the design was likely to print properly and whether the printer's settings were correct. As a result, the user may have had to adjust their design or print settings.

Step 5: Print the Model

After the validation step and any resulting changes, participants were finally able to print their model. Any issues not caught by the verification step resulted in the failure of the printing step. If the user's print failed or did not match their design intent, they would have to adjust either their model or print settings to correct the issue, often with the operator's assistance. When the casual maker was satisfied with their final model, they were not likely to pursue another 3D printing endeavor for a while. Unlike the fabrication experts who engaged in many projects requiring the use of 3D printing and modelling (often in immediate succession), casual makers had more of a one-time or short-term engagement with 3D printing.

CHALLENGES IN 3D PRINTING WORKFLOWS

As we uncovered the typical workflow in casual makers' 3D modelling and printing activities, we also became aware of a number of challenges that these casual makers faced in every stage of the workflow. We saw four key themes related to these challenges: dealing with false starts, using complex modelling software, understanding the 3D domain, and matching output with design intent.

Dealing with False Starts

Although casual makers' attempts to get involved with 3D printing were initially enthusiastic, our interviews indicated that there were many barriers to entry, especially in a casual maker's planning (Figure 1.1) and first steps (Figure 1.2A).

In contrast to fabrication experts, casual makers reported an aversion to planning out their models in any detail prior to using the 3D modelling software, even in situations where it led to multiple false starts or trial and error iterations:

> *I just started drawing in the software. I actually have started over many times, like, "This doesn't look good. Start fresh." ... If it doesn't work out as I want, I just start from the beginning. (P9)*

Casual makers often made naïve assumptions about what software would be suitable and found it difficult to select appropriate software tools as there were many 3D software options optimized for specific purposes. This confusion contributed to the highly varied software tool choices described earlier. For example, one user selected Cinema 4D since he was aware that a television show that he enjoyed used it:

> *Since I'm not really familiar with 3D software the only thing drove me to Cinema 4D because I knew that his TV show that I watch uses Cinema 4D in order to make animated scenes. This is the only reason I went and got it. Like, there's a lot of options so I don't know which one should I choose. (P12)*

Early in the casual makers' learning process motivation appeared to be very fragile. All the operators we interviewed observed that early failures, even when they were not the casual maker's fault (such as a printer hardware failure), could result in casual makers completely giving up. As seen in other studies of learning complex software [15], we observed that casual makers also had a hard time maintaining motivation once they had a false start. For example, one of the casual makers explained how he gave up when faced with instructions that required more unfamiliar math formulae or programming to create a desired custom object:

> *It [the tutorial] would get into the parts where it was like, "well, if you put this diameter and this ratio whatever." And I was like, "Nope! I'm done – Can't do that!" ...I'm a new person, and I can't understand half the things you're saying, even if you're not having math in it. (P10)*

In summary, our casual maker participants were rarely enthusiastic about 3D printing as a long-term hobby and many of them would not want to invest in further learning after experiencing false starts.

Difficulties in Producing 3D Models

Creating a Digital 3D Model

After a casual maker had decided what they planned to do (Figure 1.1) they had to produce a 3D model. Participants who opted to create their own 3D model (Figure 1.2A) had to overcome a few challenges. A number of these were common usability issues [23] experienced due to the complexity of the modelling software interfaces. However, we observed additional difficulties among participants due to the fundamental nature of the 3D space. The addition of a third dimension appeared to break many of the previously formed mental models from familiar 2D software:

> *It's hard to understand why it's [rotating] it this way, why the control is mapped with this particular way. I'm used to 2D. I don't understand... I think there might be some standard, which I don't know. (P5)*

We also observed that casual makers transferred their mental models from 2D software to 3D, resulting in difficulty aligning objects in 3D space. This misalignment occurred due to a failure to account for depth, which was not present in 2D software. One operator gave the example of a new user tying to build a snowman in *TinkerCAD* (shown in Figure 3):

> *So she brings in 3 spheres into TinkerCAD and then she brings me over and says, "Can I print this?" I'm looking at it, and I see little blobs sitting on top, and I swing it around and what she had done was placed one behind the other…when you look straight on, it looks like they were connected, but they weren't. They weren't one on top of each other, they were one behind each other. That to me was a rare revelation…you realize just how hard it is just for people to think in 3 dimensions. (O2)*

Users also reported losing track of objects in 3D space. For example, a 2D concept of space makes it difficult for users to locate objects that could become positioned behind the camera view. Casual makers also reported having difficulty in breaking down the task of building an object in 3D space into individual operations. Even when the software's individual tools were understood, properly composing an object using the tools in concert often eluded new users:

> *They don't know where to start… How do you go about dissecting a simple object, or building up an object, is not in their skillset. They don't really have the problem-solving skills. (O3)*

This difficulty may be due to the way casual makers conceptualized the construction of a 3D model. In some interviews, casual makers indicated that they approached 3D modelling as a series of 2D operations or drawings. Even users who were relatively successful reported conceptualizing 3D modelling tasks as a series of 2D operations:

> *When I create a 3D object…it was basically doing 2D drawings and then extruding them and reorienting them and basically taking what was familiar and expanding on it. (P7)*

These issues often required the assistance of a print center operator or fabrication experts. Other than navigation difficulties, these issues were often only caught as part of a final pre-print check by the operator. Since many casual makers did not even know that something had gone wrong (or exactly what had gone wrong), the operator had to explicitly demonstrate the problem or solution:

> *I actually had [an operator] sit down and kind of help me out, because I'm like "Oh, you've got to help me because I'm floating in space and I can't get down to the ground." […] [The challenge] was just navigating and knowing that I'm down here and not up here and way down there. (P16)*

One drawback was that casual makers' access to operators was limited both by the operator's time and the user having to visit the print center to seek help. Furthermore, unlike makers who were part of a network of expertise, casual makers typically lacked access to experts in the 3D modelling or printing domain. One operator described the situation:

> *There's no one here who's an expert on 3D modelling at the library. I'd say [the IT specialist], who you spoke to earlier, knows the most about it...even he is not an expert. (O5)*

This lack of formal expertise among operators made troubleshooting issues related to software functionality and the 3D

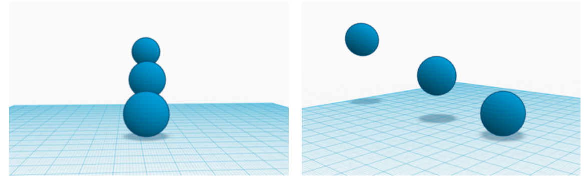

Figure 3: Challenges in aligning objects in 3D while modelling.

domain even more difficult for casual makers.

Issues with Premade Digital 3D Models

As mentioned earlier, rather than modelling an object from scratch (Figure 1.2A), users sometimes downloaded premade 3D models from the web (Figure 1.2B). Operators mentioned that they usually introduced Thingiverse to casual makers in response to their frustrations with modelling software:

> *Some people don't really understand that designing something in 3D is different than designing something in 2D. There [are] more dimensions. After they learn that, they feel defeated and go to Thingiverse instead and choose something. Then…once they've chosen something from Thingiverse, sometimes some things print better than others. (O5)*

This "download and print" workflow was presented as a simpler alternative to modelling, where instead of a user designing and modelling new objects, they instead downloaded a publicly available model. Although many operators praised Thingiverse as a tool for quickly demonstrating 3D printing to new users, Thingiverse was not universally favored among the operators. For example, one concern was that the site's homepage and overall design tended to showcase "featured designs" which were highly complex prints by experts (not amenable for learning). Some operators described how this showcasing of complex 3D models printed by expert users further gave casual makers false expectations:

> *Thingiverse users are showing off, and you don't show off with something simple. Mostly what's on Thingiverse isn't that useful within this [learning] context. (O3)*

Some previous studies [2,36] have shown the potential for users to customize and learn from existing community-created models, an activity known as *customizing* or *remixing*. However, we did not observe successful customizing behavior in our study. Of the 11 casual makers in our sample who had used Thingiverse, 8 simply printed the models as is, while 3 had attempted to customize the downloaded model with no success. Some casual makers we interviewed were unsure if customization was even possible, while others had attempted to customize but were confused by the geometry produced (see Figure 4) when they imported the downloaded STL file into their program.

> *I opened the file and the way it's structured… I don't know what's happening, like how somebody even modeled that. So I'm really going to have a hard time changing it. (P6)*

One operator described the problem:

> *Thingiverse is, for one thing, it's often STL files, which are pre-compiled into triangles for the [printer software], so you can't really get the design intent back out of it unless*

you have the same software that they use, and they happen to upload their source file [...] which they often don't. (O6)

Our fabrication experts explained that Thingiverse does have some capabilities for creating objects that can be customized on-site. However, this capability requires the user to employ a specific modelling tool (*openSCAD*) and build the model in a very specific manner, meaning that only a small portion of the models on Thingiverse had this functionality. Furthermore, these models were not freely customizable and could only be customized in ways predefined by the original author, often making them unappealing to our participants who had a specific custom need in mind.

Matching Output with Design Intent

Regardless of whether a casual maker created their own 3D model or downloaded a 3D model, they had to first process their model for 3D printing (Figure 1.3). Decisions made in this step, along with decisions made in what the user modeled (Figure 1.2A) or what the user selected to download (Figure 1.2B), affected the object's printability.

Our interviewees described 3D printers as complex devices, with operation settings that must be configured by the user, including settings such as speed, infill density and temperature. Difficulty evaluating the effects of these settings have been documented in prior work [25] and were not the focus of our study, but we did observe that casual makers had particular difficulty in designing objects that were viable for fabrication. For example, one operator explained how he tried to tell end users that a 3D printer was not a "magic device" that could print whatever he wanted on the screen:

I think when people come in, often the first time they want to print something, trying something impossible is kind of common. They want to print a huge thing the first time, or they want to print a bunch of things at the same time […] It's usually the first hurdle of understanding, even after the training sessions that we do, that they maybe want to come in and print something kind of crazy. (O8)

As our fabrication experts and operators explained, not all 3D models are easily printable. While 3D printing simplifies fabrication of many forms, it still has constraints that are not easily understood by newcomers. Small changes in geometry or object orientation affect print quality, and whether a print will work at all. For example, one fabrication expert showed us an example (see Figure 5) that the object on the right would print easily and accurately on most FDM printers, while the object on the left would be considerably more difficult. Geometric factors influencing printability included the object's base size, the presence of overhangs or thin sections, and the size of horizontal cross-sections. A new user's lack of a design-for-manufacture mental model resulted in difficulty in understanding printability of even such simple objects.

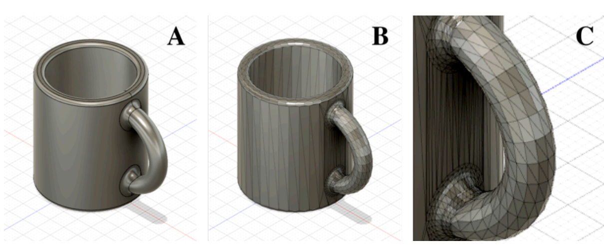

Figure 4: The native format model (A) contains complex curved surfaces, allowing them to be edited as a whole. However, when the model is exported as an STL mesh (B) the resulting geometry is broken down into many small triangles (C), preventing easy editing.

The most frequently reported difficulty was with *overhangs*, a term used to describe parts of objects that were not adequately supported while printing, as described by one of our experts:

[FDM] printers can't print on top of nothing – you need something under the bit you're currently printing to hold it up. This means that if you wanted to print a long bridge, or a man with his arms straight out in front of him, it would look really ugly or wouldn't work at all without some sort of support. Short distances are OK, but without something holding up what's being printed it usually won't work. (E2)

Our casual makers reported that they had difficulty understanding and designing with these constraints in mind and one of our operators further explained casual makers' interactions:

Sometimes we'll look at their file and say "It might be a good idea to add supports". But the supports and the raft add time, so often they turn them off without really understanding… that can produce a bad print. I'd rather it go over 15 minutes and that they have supports and they walk away happy then have the print go bad. (O5)

FDM printing processes also often leave small blemishes or distortions on printed objects, such as seam marks, layer marks, or warp. While fabrication experts knew to expect these, or used alternate 3D printing processes where appropriate to avoid them, casual makers were often surprised at these surface blemishes on their printed model:

When it prints, the material has to go up, so there's a seam line of where it went up. Sometimes that's an issue for some people. […] Somebody was printing a little Iron Man that stands about [5cm] big. Then there's a lot of overhangs. […] It was enough that it was warped a little bit, and [the user] was really unhappy with it. (O9)

With FDM printers, geometric constraints relating to overhangs and base size can be partially addressed using automatically generated scaffolding known as supports and rafts. Operators described a number of difficulties that casual mak-

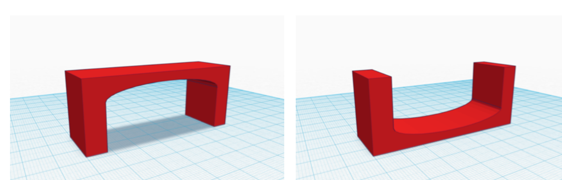

Figure 5: Small changes in geometry affect print quality.

ers faced in understanding when these features would be required. In an attempt to smooth these difficulties, many print centers enforced final check-overs by the operators on users' designs and print settings before printing to reduce failed prints. Casual makers often did not realize that they had made a mistake, and depended on operators for this check-over, and for guidance on how to design more viable forms or choose more suitable print settings:

> *People forget to add supports to their designs if there are overhangs on them. Then they just fall right to the build plate. They'll be disappointed. Sometimes they'll be here for a while because I'll be on lunch or something and then I'll come back and they'll be like just add supports and it will be fine. They don't want to redo it…(O5)*

However, even operators were sometimes not able to troubleshoot due to their limited formal training in 3D printing, leading to difficulty in evaluating printability. In the 3D printing workflows, casual makers often failed to realize that the decisions they made in producing a 3D model (Figure 1.2) would influence their success further on in the workflow. While operators provided some support, their lack of expertise and limited availability meant that casual makers still encountered errors, requiring them to return to earlier points in the workflow and contributing to increased frustration.

Given these difficulties, we asked casual makers if they had tried out online commercial print services (*e.g.*, *Shapeways*[4]). These services allow users to upload 3D models to be printed by professionals using high-end machines, freeing end users from having to learn the mechanics of a 3D printer. However, to our surprise, these services only came up in 1 interview with a casual maker and 1 with an operator. These interviewees cited the high cost of these professional services and long waiting times for printing and shipping (often, over a week) as current deterring factors.

DISCUSSION

We have contributed an in-depth analysis of casual makers' interactions with walk-up-and-use 3D printing services, illustrating their typical workflow and highlighting the barriers that they faced in every step of the process. We now reflect on these findings and highlight opportunities for improving casual makers' interactions with fabrication tools.

The Importance of Casual Makers as a User Group

Previous work [15] suggests that software learnability can be affected by user characteristics, such as level of experience with computers, level of experience with the interface, quality of domain knowledge and experience with similar software. In the context of 3D printing, we also found that these characteristics affected how well our participants learned new modelling software and 3D printing workflows. However, our study further shows that motivation and engagement are important characteristics that differentiate casual makers from other makers and enthusiasts. Whereas makers and enthusiasts are motivated by a desire to learn and experiment with new technology [21], the casual makers that we observed were more concerned with output and were likely to abandon 3D printing if the initial learning barrier was too high and they did not get their questions answered. These casual makers were more likely to give up after false starts and often did not want to make a long-term learning commitment. But, surprisingly, casual makers were still not enthusiastic about simply using premade models or online 3D printing services and showed a strong desire to be able to create custom objects using walk-up-and-use printers. These results suggest that there is a lot of potential in HCI to better understand and support this emerging user group of casual makers to complement efforts on supporting makers, enthusiasts and professional users.

Print Centers are Different from Makerspaces

Another key observation that we made in our study was that the print centers where casual makers went to use 3D technologies lack the strong sharing culture and informal network of expertise of makerspaces. In print centers, users sought help only from operators, who were often not formally trained in 3D printing. Unlike makerspaces, we did not see evidence of sharing completed projects for peer learning in that casual makers were more transient: they completed a project or experimented using the print center and then moved on. Rather than the peer-to-peer community of expertise exemplified by the original makerspaces, these print centers tended to form a much more hierarchical network similar to more traditional help and support structures [21]. Similar observations have been made in online hacking forums where there are tight-knit communities that collaborate extensively each other while others form looser collectives and users come and go without long-term engagement [52].

Shared Models Tackle Only a Part of the Problem

One of our key findings was that casual makers struggle the most in understanding the 3D domain, and current commercial tools have limited provisions for helping users understand the underlying domain. It is not surprising that we are seeing the emergence of tools (*e.g.*, Thingiverse) that allow users to share and contribute models so that they can bypass the modelling step. But, as explained before, casual makers and operators were not always satisfied by the experience of using Thingiverse as it was difficult for them to understand if a downloaded model would actually be printable on a walk-up-and-use 3D printing station. This illustrates a larger theme in our findings about the interdependency between the different stages of 3D printing worklow.

Perhaps the bigger issue that deterred some casual makers from using premade models was the lack of flexibility in customizing models. Many of them had tried to download and customize models, often with little or no success. Model sharing as a whole appeared to be limited by the existing practice of sharing STL formatted models as opposed to richer interchange formats. Future research may seek to answer why this practice occurs, and how users sharing models

[4] http://www.shapeways.com

might be motivated to upload richer formats. Even though customization tools, such as Thingiverse's Customizer and data-based fabrication tools [19,35] are being explored, we found that casual makers' customization needs were often driven by highly specific and idiosyncratic goals for which there may not always be a suitable model available.

Design Opportunities for Fabrication Tools

Although new HCI innovations are already simplifying and streamlining complex fabrication processes, we discuss two design opportunities that could facilitate the workflows of casual makers.

Supporting the Interconnected Fabrication Workflow

A key focus in the HCI community has been on making the 3D modelling step easier for end users, which we observed was a key challenge for our participants. For example, projects as early as *Alice* [8] have worked to simplify how users understand 3D spaces. More recent innovations in augmented reality [54] and virtual reality [20] show promise in simplifying understanding the 3D space. Sketch-based interfaces (*e.g.*, *Teddy* [18]) and gesture-based interfaces (*e.g.*, *Paper3D* [38]) have demonstrated ways of expressing 3D forms. However, as discussed above, we observed a strong interdependency between the different stages of the 3D printing workflow in that casual makers often struggled not only in creating models, but also in understanding how the model geometry affected output, or how print settings affected output.

Although recent tools such as *Meshmixer* [45] offer the potential to understand basic qualities of 3D printed output, such as overhang or balance analysis, we did not observe such tools to be in wide use at print centers as at present they still require significant domain-specific knowledge. There has been some exploratory work [11] that uses simulation of fabrication artifacts to visualize fabrication output, or uses interactive guided tools that help end users build more viable objects, such as structurally sound furniture [51]. There is potential in further exploring this space that can help casual makers better connect their design intent to output. Perhaps there could be "preview" techniques built into fabrication tools that would allow end users to actually experience their final printed objects and modify them on the spot. One promising research area is interactive fabrication, where the user's object is constructed in real time as the user models it, allowing the user to immediately see the relationship between their 3D model and fabricated object, [32,56]. The insights from our study on the behaviors and practices of casual makers can further inform the design of such innovations in connecting digital fabrication workflows.

Interweaving Expertise in Fabrication Tools

Even when tools succeed in providing support for the interdependent nature of the 3D printing workflow stages, our findings suggest that these would have to be simple enough so that the casual makers who did not want to make a long-term investment in learning would actually benefit. Furthermore, one issue that we observed in the study was that almost all of our participants were deeply dependent on print center operators to bootstrap their 3D printing workflow and to troubleshoot. Given our observations, we believe that this dependency will not easily go away even if we improve the usability of fabrication tools because of the output-driven custom needs of casual makers and lack of interest and time in gaining expertise in the underlying domain. Therefore, we have to view 3D printing for casual makers as a highly social activity and there may be numerous opportunities along this path to support casual makers' workflows. For example, it may be possible to "weave in" expert tips, advice, and explanations throughout the printing workflow. Expertise-sharing systems have a long history in HCI [1] where information is shared in a way such that the expert is an "intangible" actor in the interaction.

Some recent tools have already started exploring ways of helping users share expertise and learn socially within web-based and desktop software applications [7,26] as well as within programming environments [17]. But, for the population that we studied, the useful information would not just be about troubleshooting software or hardware internals, but also about best practices and domain-specific nuances and "tacit ways of knowing" [40] that can take years of experience to develop. In particular, since print center operators were lacking the kinds of community expertise prevalent in makerspaces, there may be opportunities for them to connect virtually and in-context of where end users and other operators need help and advice.

Limitations

Snowball sampling may have introduced bias by over-sampling from specific communities. We looked for users who have recently attempted 3D modelling and printing, regardless of whether they were successful. However, users who were not successful may be less likely to come forward. Additionally, our sampling excludes users who were deterred from ever attempting 3D printing due to the perceived difficulty. Future work may look into other recruiting methods in an attempt to capture a wider range of experiences.

CONCLUSION

Current research and popular press suggest that consumer-level 3D modelling and printing are challenging, but one contribution of our paper is in highlighting where exactly the challenges lie in the casual makers' workflows and how this class of consumers is different from makers and enthusiasts. Furthermore, we show that print centers are different from traditional makerspaces, lacking access to the networks of expertise that have made the latter popular among more experienced users. We recommend that future fabrication tools consider the interdependencies within a casual maker's workflow and the social nature of the walk-up-and-use 3D printing process.

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