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Appropriating Digital Fabrication Technologies – A comparative study of two 3D Printing Communities

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Abstract
Digital fabrication technologies have a great potential for empowering consumers to produce their own creations. However, despite the growing availability of digital fabrication technologies in shared machine shops such as FabLabs or University Labs, they are often perceived as difficult to use, especially by users with limited technological aptitude. Hence, it is not yet clear if the potentials of the technology can be made accessible to a broader public, or if they will remain limited to some form of "maker elite". In this paper, we study the appropriation of digital fabrication on the example of the use of 3D printers in two different communities. In doing so, we analyze how users conceptualize their use of the 3D printers, what kind of contextual understanding is necessary to work with the machines, and how users document and share their knowledge. Based on our empirical findings, we identify the potentials that the machines offer to the communities, and what kind of challenges have to be overcome in their appropriation of the technology.
Keywords: Appropriation; infrastructuring; empirical study; 3D printing; hardware-related context.
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1 Introduction

Until recently, digital fabrication technologies like 3D printers or laser-based cutting machinery could only be found in specialized industrial companies with expert staff trained in modeling, fabricating and finishing professional artifacts and prototypes. Recently, there has been a proliferation of Do-It-Yourself (DIY) communities that can be viewed as part of a larger, global maker movement and the shift from professional to private: Hackerspaces, FabLabs, and Shared Machine Shops establish themselves more and more. As the propagation of digital means of construction has eased the ways of end user production and adaption of technologies formerly reserved for specialized companies, the DIY movement has even more potential for innovation. Research indicates that digital fabrication technologies significantly influence and change the landscape of personal fabrication (Mellis & Buechley, 2012). Those technologies are tied to Maker and Do-It-Yourself (DIY) communities which have been researched in a wide range of contexts, not only limited to digital fabrication, ranging from DIY biology (Kuznetsov, Taylor, Regan, Villar, & Paulos, 2012) up to the fabrication of complex personal electronic devices (Mellis & Buechley, 2012). Some people assume that in the future, digital fabrication technologies might be available in every household (Wittbrodt et al., 2013). Even though such visions might be a bit optimistic, there are already examples of very useful innovations that have been driven by end-users, for instance the development of cheap and adaptable prostheses for disabled children or concepts for upcycling and waste reduction in the context of urban gardens and other domains.

Digital fabrication technologies have a great potential to foster user driven innovation and promote alternative economies. Often though, technology-driven maker communities associated with FabLabs or Hackerspaces are still perceived as places for people who are knowledgeable about technology and have difficulties to maintain an open dialogue with society at large. At the same time, the experimental nature of digital fabrication technologies such as 3D printers makes their adaption and appropriation challenging. Learning how to use (and fix) such machinery can be quite difficult, but also empowering for the users. Hence, attracting a more diverse clientele as well as a sharing innovations created by users are still seen as the main challenges, and it is not yet clear if and how the potentials of the technologies can be made available to the broader public. In order to get a better understanding of how digital fabrication technologies – such as 3D printers and laser cutters – are currently appropriated and used in the wild by different maker-related communities, especially from the perspective of new users, we conducted an empirical study in two different communities: a) a community of HCI researchers at our home university, and b) a community of artists at a German Academia of Media Arts. In our paper, we provide a detailed account on how the users of digital fabrication technologies in the different communities use the 3D printers, how they share knowledge about them, how they appropriate them and which roles the machines play for their creativeness and understanding of technology within the communities.

2 Related Work

From a theoretic perspective, appropriation can be understood as the discovery and sense making of an artifact (like a 3D printer) while using it in practice Pipek (2005). This understanding has its roots in established Computer Supported Cooperative System (CSCW) and Human Computer Interaction (HCI) literature, where appropriation is associated with the process of fitting new technologies in users' practices in situ by adoption as well as adaptation of those technologies (Balka & Wagner, 2006; Dourish, 2003; Mackay, 1990; Stevens, Pipek, & Wulf, 2009). The concept of appropriation goes deeper than that of customization and similar notions in software development in that it can encompass fundamental changes in practice and embraces the possibility of users adopting and using the technology, even in ways never intended by its designer (Pipek, 2005). Furthermore, it has to be noted that appropriation is associated with processes of exchange and interaction in social networks of co-users where experiences and stories are shared between actors involved in the appropriation process (Gantt & Nardi, 1992; Mackay, 1990; Pipek & Kahler, 2006; Pipek, 2005). The firm grounding of appropriation in doing, i.e. using the respective artifact and transforming it if need be, can be viewed as relating rather closely to the DIY and maker communities which utilize similar frames of mind and strategies when approaching new technologies (Kuznetsov & Paulos, 2010b; Tanenbaum et al., 2013). This article examines how the individual end users actually deal with the 3D printer, how they appropriate it and how they solve problems and share generated knowledge:

Doing things yourself, on one's own initiative with one's own hand and head involved is probably one of the oldest and most natural activities of human nature, starting with DIY hand tools in the Stone Age. Yet, the evolution of industrial production and economic systems has shifted almost all manufacturing away from the individual towards large-scale production centres and external services. Generally understood as the industrial revolution, the introduction of machines for automated production and division of labour marks an important step in the historical development. However, parallel to increasing technological advances, a culture of making things oneself not just out of pure necessity but also for joy and fulfilment has developed and gained momentum starting in the second half of the 20th century until today.

Recent surveys from diverse countries around the world show that consumers spend significant portions of time and money to create and modify products for their own use. They demonstrate that do-it-yourself (DIY) is not just a marginal phenomenon, but is of increasing economic and societal value. Users, as being closest to the products they use and knowing best the needs and expectations associated with them play an important role for advances and innovation, especially in fields generally considered niches, and thus not pursued by big industries (Hippel, 1988).

In its modern understanding, the DIY movement has been around since the 1920ies (Kuznetsov & Paulos, 2010a) starting with a hobbyist radio culture and later predominantly spanning activities associated with the personal home. It can be interpreted as a re-appropriation of household skills that have been outsourced towards external suppliers in the course of the industrialization (Hagemeister, 2009). In contrast to homework which is rather focused on economic aspects such as cost saving (in the sense of a "make or buy decision"), and meeting individual needs, Making in the new sense can be seen as an empowering experience which can be supported by new models of communication in communities where it is easier - and socially honoured - to share self-made creations and related innovations. It is very much connected to the communities of hobbyists and crafters that the home computer industry was spawned (Campbell-Kelly, Aspray, Ensmenger, & Yost, 2013; Glenn Blauvelt, Tom Wrensch, 2011).

Possibilities for broad influences of digital fabrication technologies once available to a general public are viewed as the next step in the digital revolution with similar disruptive potential as the introduction of the personal computer (Gershenfeld, 2012; Mota, 2011). However, while how to include emerging digital fabrication technologies in the educational system and how to make children acquainted with them is increasingly being discussed (Dlodlo & Beyers, 2009; Eisenberg, 2007; Posch & Fitzpatrick, 2012), how to attract a general public to take part in the discussion about current technological developments and enable them to become active users is studied much less. In this regard, many obstacles are to be overcome in order to even approach a level of prevalence of digital fabrication technologies comparable to that of personal computers: The rapid advancements in those complex technologies (Gershenfeld, 2012) and their swiftly growing presence in new domains like those of hobbyists (Tanenbaum, Williams, Desjardins, & Tanenbaum, 2013) are seen to warrant or even necessitate corresponding advances in interfaces and other tools to support the usage and appropriation of these new technologies (Avram, Boden, Posch, & Stevens, 2013; Sadar & Chyon, 2011; Williams, Gibb, & Weekly, 2012).

The development of end-user oriented digital fabrication technologies such as 3D printers has been driven by various communities in the fields of open hardware (and open source software). DIY and maker communities in FabLabs and Hackerspaces have also been the first to adopt the new technologies, which can nowadays also be found increasingly in contexts such as schools and universities. Although the communities from all fields overlap to a large extent, they can still be analytically separated and often the members themselves insist on the separate identities of the communities (Maxigas, 2012; Moilanen, 2012; Tocchetti, 2012; Troxler, 2010). For instance, Moilanen & Vadén (2013) group the different people engaged in 3D printing loosely into three categories in terms of technology adoption.

1. *End users* print objects and artifacts with 3D printers and mainly use 3D printing services, but are not involved in development.
2. *Early adopters* buy 3D printers and use them with the help of the community, in the process making contributions, software or hardware to the communities. Such contributions could e.g. be test results with different kind of printing speeds, experiences of how different printing materials behave on printers or about particular hardware modifications.
3. *Developers* mainly focus on the development of the entire 3D printing process on a hard- or software level.

Moilanen & Vadén (2013) show that in terms of creating and upholding artifacts, the friction introduced by the physical nature of 3D printing does not fundamentally change the mode of operation compared to open source software, but it is much slower, harder and more complex to develop and share artifacts. Especially the end users mainly use 3D printing services, where the early-adopters as well as developers have fewer problems operating the printer. An interesting question is therefore if a new "3D printing elite" will emerge and what has to happen in order to empower more end users to learn how to appropriate a 3D printer and how to handle the entire 3D printing process on their own. After all, the growing availability has led to a situation where more and more users are engaging with digital fabrication who might lack the knowledge of the "early adopters" in terms of technical and conceptual understanding of the machines, which might make their appropriation challenging.

3 Application Field

To get insights into the current practices of 3D printing processes and how appropriation works in such contexts, we first have to understand the contemporary uses of 3D printers, including the modeling, the printing itself and the finishing of artifacts and prototypes in the different communities. Therefore we conducted an empirical study in two different 3D printing communities. The first is a community of Human Computer Interaction researchers at a German University (HCI-UNI). Two Fused Deposition Modeling (FDM) printers (MakerBot Replicator Dual and Replicator 2X) and one full color powder composite printer (ZPrinter 650) are available. These are located centrally in a so called HCI-Laboratory (**Error! Reference source not found.**, left, see also http://hcilab.wineme.fb5.uni-siegen.de/), where, beside the printers, also soldering iron stations, a drill press as well as other tools for manipulating hardware are on hand. The HCI-Laboratory is also used for team meetings or project groups, but is frequented regularly by students as well. The second community is one of artists at a German Academia of Media Arts (HCI-ART). They have just one FDM printer (Replicator 2). It is located in an outbuilding which is only attended for printing purposes (**Error! Reference source not found.**, middle and right).

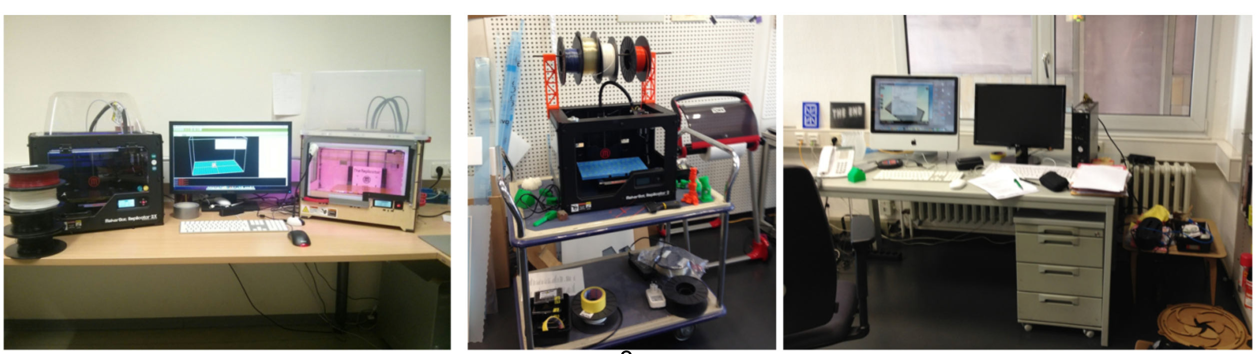

Figure 1: 3D printer environments: HCI-UNI (left) and HCI-ART (middle, right)

For our research, we understand these communities in the sense of the concept of Communities of Practice (CoP), which are “groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly“ (Wenger, 2009). CoPs are not a recent phenomenon, even if the term is still relatively young. Already in early years there were ‘informal communities’ that shared their experiences with each other: in the Stone Age, hunters shared their experiences made during the hunt and in ancient times, groups of craftsman and physicians aspired to disseminate the education and training of new techniques (Zboralski, 2009). A CoP is characterized by a shared domain of interest. Involvement includes a shared competence that distinguishes involved ‘members’ from other people. However, the domain is not necessarily something that is perceived as expertise outside the community. To increase the interests and knowledge in their domains, involved members engage in activities and discussions, help each other and share information. They build relationships that enable them to learn from each other. Its members are mainly practitioners: They develop a shared repertoire of resources such as experiences, stories, tools and ways to deal with recurring problems (Wenger, 2009).

The view on the field was sensitized by our design intention. We conducted a Grounded Theory oriented approach (Gantt & Nardi, 1992), where we did not explore the field with predefined categories, but derived categories from empirical data. To reconstruct the practices we used observations, workshops as well as interviews. The observations (10 hours, both communities) were used to acquire knowledge about practical work in 3D printing and its process. The workshops (2 workshops, 2 hours each) allowed us to understand the communicative practice of printer-specific knowledge and information sharing. The interviews (Table 1) allowed us to analyze the work context and the use of printing tools and communication systems of relevant users. The semi-structured interviews lasted about one hour each and followed a guideline which evolved from the field and was separated into three parts: The first part focused on the participants’ role in his working context, the qualification, tasks and work steps with 3D printers. The second part covered the handling of such hardware concerning entry obstacles, how the user got into 3D printing, which problems exist, and if and how those are articulated in the community. The third part covered the process of modeling artifacts, including related problems and utilized tools. The questions as well as the structure of those interviews were derived from the previous fieldwork (the workshops and observations). All interviews were recorded and transcribed for later data analysis.

No.	Role	Community
I01	Research Associate (PhD student)	HCI-UNI
I02	Senior Researcher (Post-Doc)	HCI-UNI
I03	Research Associate (PhD student)	HCI-UNI
I04	MA student Human Computer Interaction	HCI-UNI
I05	Senior Researcher (Post-Doc)	HCI-ART
I06	Head of experimental imaging (Post-Doc)	HCI-ART
I07	Engineer and artist	HCI-ART

Table 1: Interviewees

4 Example Projects

In this section, we will briefly present some example projects in order to provide context to the findings (section 5), where we will provide a detailed picture on how the printers are used.

4.1 Printing Minecraft Models (HCI-UNI)

The 3D printing Minecraft models project was conducted in the context of the come_IN[1] research project from the University of Siegen which is interested in how children can be engaged with computers based on constructionist principles (Harel & Papert, 1991) and bond with each other for joint learning in virtual environments (Stevens, Boden, & Rekowski, 2013). One of the computer clubs of the come_IN network engaged in a project with the game Minecraft which was used as a virtual environment for collaborative construction. The models that were created during the project were exported from the game and printed on the ZPrinter 650 in the HCI lab for a school exhibition. The exporting and printing process was carried out by researchers at the University (after discussion with the children), but the modeling was done

[1] http://come-in.wineme.fb5.uni-siegen.de/index.php?id=en [Accessed: 19.12.2014]

exclusively by the kids and helped them to better understand and form a different relationship to the artifacts that they created in the game. Based on fieldwork during the project, the researchers analyzed how children created 3D models cooperatively, and how the transition from the virtual to the physical artifact changed their interaction practices.

Figure 2: 3D printed Christmas decoration, designed in Minecraft (left); a group of children playing Minecraft (right).

4.2 The HackDock (HCI-UNI)

This 3D printed notebook docking solution was developed as a design project for a class on user experience by a student of the University of Siegen. The student was annoyed with having laptop cables lying all over his desk as well as with having to plug in or unplug all those cables every time he wanted to take his notebook with him. Inspired by the possibilities of the HCI lab at the University of Siegen, he decided to design a cheap and simple solution utilizing DIY and Maker methods that would allow him to handle all cables at once: The HackDock.

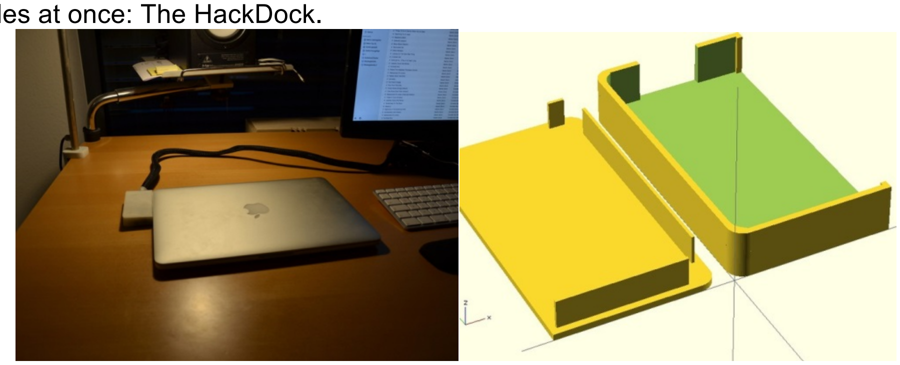

Figure 3: The HackDock in use (left) and as a model (right).

The HackDock was printed on a MakerBot 3D printer. The student also shared his model on Thingiverse[2] and set up a webpage that explains the purpose of the project and provides instructions on how to print and assemble the dock[3].

4.3 Hybrid Design (HCI-ART)

The research projects of the artists of the Academia of Media Arts in Cologne are quite multifaceted. They range from student projects with specific given topics like “designing a landing field for aliens” to the design of hybrid spaces. The artists presented an exhibition with the title „Hybrid Design – Autonomous Cell Space” at the Beijing Design Week in 2011 (Goethe Institut, 2011). In the center of Hybrid Spaces are DIY practices concerning 3D printers. “Hybrid Design” focuses on those design areas that have evolved from the combination of environments, objects and services in the age of information technology. They presented two video installations and a sound-installation that deal with the idea of feedback in spatial perception through digital media technology.

[2] http://www.thingiverse.com/thing:143146 [accessed: 19.12.2014]
[3] http://scriptogr.am/oliverstickel/the-hackdock [accessed: 19.12.2014]

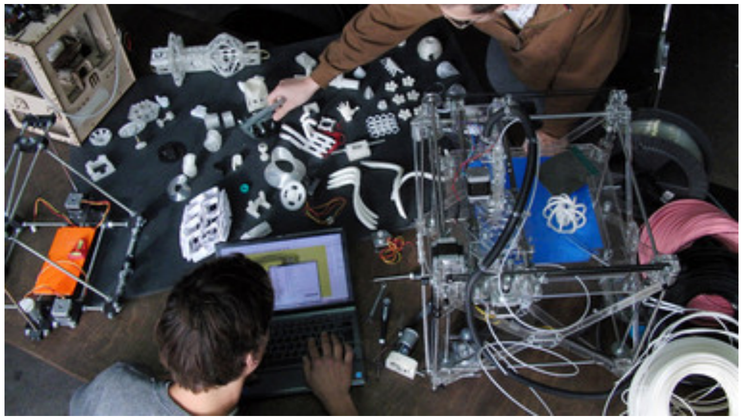

Figure 4: Insights „Hybrid Design – Autonomous Cell Space" (Goethe Institut, 2011)

5 Empirical Results

5.1 Emergence and self-conception of the printing communities

> "Since I've been at the [Institution Name], there always was a need to transform the virtual, to make objects, especially if you work with 3D and we had different processes for that, we started to make paper patterns to cut sheets with and, so to speak, to transform 3D objects into polygons, into sheets into sculptures. The next step was essentially to print things via print on demand services like Shapeways. And eventually, [inspired by] the most recent Makerbot, we felt the need to actually have a printer with us in our lab." (I06)

> "We collaborate with firefighters and develop tools for communication and coordination. We develop quite close to the hardware and accordingly, I was quite interested in our Replicator by the time it was finally here. I was also interested immediately because you can print your own, customized casings [for the communication tools developed in the project] quite quickly. As a result, I quickly learned how to use it and that was how I appropriated it. The big 3D printer [Z-printer] here, I was involved in acquiring that, too, that was in the course of a project top-up of a previous project which also dealt with firefighting." (I03)

For the HCI-ART community, it was frustratingly hard for students and artists to build free, three-dimensional shapes and thus explore the spatiality of their art. HCI-UNI needed to build and deploy custom casings for microcontrollers, sensors and other hardware designed to be carried by firefighters. Both communities first tried to work with external companies – HCI-ART used 3D-printing services while HCI-UNI had casings manufactured traditionally (i.e. having custom molds built). Especially the latter process was described as very expensive and it was impossible to quickly iterate the designs and test prototypes rapidly. Given the advances in 3D printing techniques, both communities decided to buy FDM 3D printers intended to address their project needs.

> "We had this issue with the Makerbot where when we printed in PLA, the harder bio-degradable plastic, that is, that it often rattled and didn't convey the material properly […] A few colleagues were bothered by this and they started to look into what could be done and after that, they basically downloaded their own plunger from the internet, printed it and installed it and now PLA printing works well which is nice." (I02)

> "Obviously, you have ideal conditions at the [institution name] to just build your own printer and I didn't build the printers to carry out traditional 3D printing. Instead, we modified it to print with foodstuff, for example. What I find interesting with 3D printers is that you can build parts which are hard or impossible to buy and since I tinker quite a bit, I can build some adaptor or small parts for myself." (I07)

Both communities then started to make advances in understanding the technology, the modeling processes and subsequently begun to manipulate their printers themselves. On the one hand, this was due to artistic and experimental needs not catered to by the printer manufactures. On the other hand, community members tried to overcome limitations of their printers, e.g. by modifying components to better suit their needs or to construct remote servicing and monitoring tools to better intertwine the printers with their work practices. It has to be noted that especially HCI-ART recently started to branch out into the developer category by aspiring to implement their own technical solutions to supplement appropriation processes and to develop solutions on a deeper, more hardware based level. HCI-ART also followed a different model with regard to providing access to the printers, as in this institution the printing itself was usually overseen by a knowledgeable member of the department, while HCI-UNI followed a much more informal approach where every member of the group could in principle use the 3D printer(s) without a centralized gatekeeper in place.

5.2 Playfulness and persistence foster transformation

> "Then somehow over time, we got around from this hobby and side projects to learning more and more about how we can work with the thing [the printer] and also started to deal with 3D modeling, how it all works [...], how to clean the printer, maintain it and what to do when it will not work and so on." (I02)

> "What really fascinates me on 3D printing is that you can finally create something on the laptop, which you can later hold in your hands, except a hardcopy. One has the feeling of having created something, so it is not comparable to creating just a graphic on the laptop: You can touch it, which is just so exciting." (I07)

> "Every mistake you make, which does not result in the device being damaged is not bad. It's a bit like programming. If it is not working, then it is simply not working. It can be canceled very easily at any time if you tested anything." (I03).

The transformational process from end user to early adopter to aspiring developer is expressly associated in both communities with fun, playfulness and exploration. Even if, especially in HCI-UNI, the original printer purchase has been described as goal-oriented, everybody we interviewed expressed quick and affective fascination for such novel and unique tools which – unlike the usual office equipment one might find in universities – enables and empowers their users to make things which actually can be picked up and touched. Unanimously, this fascination is described as the motivational factor for persistence as well as a sort of "the proof is the pudding" (I03) attitude where a lot of learning by doing, experimentation and comparable lot of incidental errors were made and learned from without doing extensive research or reading first. Due to the different ways in which printer access was provided, these processes played a more prominent role for HCI-UNI, but they were also reported in the case of HCI-ART.

5.3 Contextual (mis-)understandings

> "It just takes a long time to figure out something like this [thermal deformation of the prints]. So, at first, it takes some prints and eventually someone notices by accident that it happens whenever we have the window open. A lot of luck is involved in noticing this." (I01)

> "The issue is always of course that the problem is deeply embedded in its own specific context. So maybe it is the particular model, maybe it is the software just now." (I01)

> "There are certain keywords like the 'raising', where everybody is talking of warping. Then you search for 'warping', 'Replicator2' and other keywords, of course. Anyway, you need the device name and then those keywords every time." (I03)

Community members sooner or later inevitably ran into problems during printing. Examples include *warping* which is thermal deformation of the printout due to uneven cooling during the printing process or issues with filament transport. Multiple users noted that discovering and most importantly, understanding and locating those problems in order to fix them proved quite difficult and often succeeded more through sheer luck than anything else. This was attributed to the complexity of a 3D printer which is considered as a tightly interconnected system of hardware, software and the human operator. Of further concern during the search for solutions was the fact that certain keywords and phrases which are used in 3D printing communities are not readily used in day to day language and have to be discovered first which proved to be semi-successful and frustrating for the search process at times.

5.4 On documentation and sharing

> "I don't use [the printer] very often and I forget a lot again, so you have to appropriate it to a certain extent all over again." (I02)

> Well, like it always is if you analyze knowledge first, that's connected with work and that's why you do it rather motivated by a sense of duty. I have never blogged with a great passion. Actually, in bulletin boards, I was mostly reading. Never really wrote anything.

In both communities, 3D printing is but one aspect of multifaceted work and play - hence, the printers are used rather irregularly. This entails the problem of lost knowledge: Users keep forgetting the exact settings they used in the prints before and the impacts these settings had on their printouts. This is further amplified by a general disinclination towards documentation which seems connected to a temporal and logical divide between the actual printer and external knowledge repositories as well as towards the extra work thorough documentation would entail.

> "Normally we are just speaking about the print itself, not about the modeling; this is at least my experience. The reason is that in the field of modeling hardly any cooperation exists. [...] This is always an individual problem. The problems you encounter during printing concern everyone who prints. Therefore there are plenty more intersections to talk to each other. I think that is in the nature of things." (I03)

> Or I was near the regular paper printer [located near the 3D printers] and printed something, a document or something and notice that the 3D printer is running and it [the printed object] looks like it belongs to [colleague's name], I might ask him later what he made. You talk at times, when there are problems.

If we want to consider sharing and democratizing practices in 3D printing, we have to consider the subdomain addressed: In our study, it became clear that 3D modeling and the actual printing process are different: More sharing and exchange happens regarding the actual printout with the 3D printer, often very spontaneously and ad hoc in comparison to the modeling process where some meta-exchange regarding choice of tools and similar abstract questions tends to happen, but the actual designing and modeling process seems to be considered a very individual task. However, given recent developments, some professional tools (e.g. Autodesk Fusion 360) as well as experimental and innovative tools utilized by the Maker community (like using Minecraft for 3D modeling), the focus on collaboration seems to grow.

> "At some point, I signed up for a Thingiverse account and placed just a few models that I have designed myself online [...] I think it is actually quite a nice feature of Thingiverse that you get a bit of feedback, that someone likes it or includes it into his Things-to-Make-Collection or writes a comment or something."

> "So you often get a lot of information about how they printed it - sometimes not. But often they write additional stuff where little instructions are located, what temperature is needed and how to position the part in the build envelope […] and often you get hints, with which material on which printer it was printed and so on. I think it is important to get some hints, especially at the beginning." (I02)

Sharing sites that are focused on 3D printing, especially Thingiverse as the most popular platform, are seen as positive and provide lots of inspiration as well as qualitative feedback in the form of comments, and likes as well as *remixing* features which focus on community-based iteration on existing models.

6 Discussion

Both communities started out their printing experiences and careers in similar fashion: They had specific needs which were hard to overcome with the help of their erstwhile equipment. Subsequently, they explored other avenues, starting out with external services which did not prove satisfactory due to negative experiences with budget, availability and accessibility. At this point, both communities could be placed in the end user realm. After that, both communities made purchase decisions for 3D printers focused on specific goals and project needs. These foci, however, broadened significantly after the communities had access to the printers as well as the chance to engage with them in depth. "Playing around", engaging with the printers in a ludic fashion and exploring their possibilities proved to be motivational factors in transcending the status as end users and drifting into early adopter territory. While both communities showed some differences in which the access to the printers has been organized, this playful fascination quickly led to the formation of CoPs and experimentation exceeding the original purchase goals in both communities. Making things that can be touched, held and experienced in a haptic, three dimensional way seems to be a substantial motivational factor for comprehensive engagement and the aspiration of learning and trying more (usually by doing). With better understanding of the printers' capabilities and sometimes technical shortcomings, community members felt motivated to engage with the devices on an even deeper level, going so far as to motivate them which can be considered an appropriation process in the maker fashion, adapting and adopting the printers into daily work and play practices in a more complex and technical way than would usually be the case with other office equipment.

There are, however downsides to consider in this appropriation process which harbor dangers of forming new "maker elites": An important issue we begun to understand during our interviews is that of contextual information and deeper understanding of the printing process. Users often struggle with comprehending printing problems and locating them, let alone fixing them which is due to the fact that 3D printers are quite complex hardware-software systems including socio-technic aspects. They also can be much more context sensitive than, say an average office laser printer, which usually will not produce faulty prints if the door is left open and a breeze cools down the room a bit which can very well happen with a 3D printer. Hence, people often perceive a 3D printer as a sort of black box which lacks in ways to inform its user how it really works and especially about the causes, context and connections of flawed prints which will happen sooner or later given the current state of technology. This is deemed especially critical at the beginning of a 3D printing career where insights into the inner workings, possibilities and sources of error is fuzzy at best, but the problem pervades even in later stages of appropriation, especially given the "the proof is the pudding" attitude mentioned before which is focused on doing rather than researching or reading beforehand. Complicating the issues further are "language barriers" met when searching for possible solutions: DIY, maker and 3D printing communities have developed a certain domain specific vocabulary (e.g. "plunger" which in this context is not used in the bathroom but denominates a small but crucial plastic part pushing plastic filament against its conveyance mechanism). This restricts easy access to informations and solutions via search engines quite a bit.

The second danger concerns documentation and sharing of knowledge and expertise: Documentation is seen as a tedious job, not dissimilar to the effect of disinclination to contribute to Wikis and similar knowledge repositories which leads to forgetting learned information as well as the compartmentalization of knowledge and expertise. This is a common problem in CSCW, but for 3D printing, it is amplified by two factors: Firstly the long time passing by between inputting the settings and examining the final print – in some cases, print time can be 20 hours or more - and secondly, there seems to be a perceived conceptual clash between formalized, external documentation tools and the inherently fluid, agile and ad hoc nature of 3D printing. Current 3D printers generally don't include any kind of matched documentation tools supporting this fluid User Experience which only serves to amplify the clash further.

Regarding sharing practices, it is notable that 3D printers seem to act as boundary objects and to actually foster exchange about the printers and the printouts, anchoring discussion. The more software related side, namely the modeling process, however, seems to spawn much less sharing which may be related to the myriad of different tools, approaches as well as highly specialized communities (engineering, 3D animation, etc.) from which information and tutorials are pulled. Generally speaking, a lot of sharing and discussions happen ad hoc, in situ and, most importantly, internally and often through the grapevine. Knowledge is often not disseminated across the boundaries of the particular, regional CoP. Similarly, if a CoP has been stagnant regarding new members for a while and the current members are stable and know each other well, they tend to form certain structures (like common vocabulary, expert roles, etc.) which can be hard to understand for potential new members of the CoP, especially if those structures and the accompanying knowledge and practices are undocumented. External sharing platforms like Thingiverse are popular for inspiration and a measure of qualitative feedback as well as a certain amount of discussion. They also can contain knowledge and best practices but there is only a rudimentary meta-structure available for this kind of information. These results in knowledge fragments distributed through a lot of sub-sites and no standardized, indexed and searchable repository. Furthermore, no quantitative, technical validation of the shared models regarding printability, model consistency and similar factors is in place (neither on the sharing platforms nor in the printers themselves).

7 Conclusion

As our empirical findings illustrate, it is especially the high context-dependence of a successful printing process that confronts the users with problems. Getting to the roots of failures and mis-prints is a complex problem area, because errors can occur at three different levels: On an (1) internal device-related level, with wrong printer configurations or settings, (2) in a socio-material context where errors result from of characteristics of the printer's location, its surroundings, and maintenance resources and (3) a task-related process context, e.g. problems with the tools used to build or prepare prints or related to a specific part of the production chain or process. The high context-dependency is very hard to master – even for professional users or experts. For users with lower levels of experience, it can be an insuperable obstacle, as it can be very difficult to recognize and describe problem sources or the reasons of mis-prints in the right language in order to be able to ask for help – especially since operating 3D printers involves a high amount of tacit knowledge (Polanyi, 1967) and practical "knowing how" (Ryle, 1949) that can be hard to make explicit. Aspects such as over the shoulder learning (Draxler, Stevens, Stein, Boden, & Randall, 2012) and situations of legitimate peripheral participation (Wenger, 1998) are important resources in this regard, as they open up the possibility to learn how to operate the machines and achieve first results for inexperienced users. At the same time, they often require a certain hands-on attitude to master complex technologies without feeling too intimidated to take first steps in a new domain. In this regard, our findings illustrate that "playful" approaches that are especially abundant in environments that follow a more informal way of providing access to the technology may have some advantages, in a quite similar fashion as has been observed in the case of the appropriation of software ecosystems (see Draxler, Stevens, Stein, Boden, & Randall, 2012).

With regard to making use of the potentials of the new technologies for society at large, we can conclude that the current situation in the communities we have studied is indeed one that is strongly driven by experienced users that have mastered the machinery and share knowledge in often personal and informal ways with each other. While on a general level, there are clearly signs of a democratization of digital fabrication technologies, our study implies that the tools (in terms of software and hardware) have to come a long way until a really broad appropriation can be achieved. As our study as well as literature and many projects showed, users can be quite creative in their appropriation of the machines, and have already begun to implement improvements that help them dealing with the technology, and that could be systematized in order to improve the usability of the machines (in fact, newer models of the MakerBot brand already come with similar built-in solutions, for example for remote monitoring). However, improving the usability of the technology is only one aspect in this context, as the high context dependency and the deep knowledge about the three contextual dimensions that we have outlined above cannot be addressed in mere technological terms. Other solutions such as letting the printers be mainly operated by expert personnel such as in case of HCI-ART is another possible solution, but it has the disadvantage that it partially limits the possibilities of the end users to affect the results of their printing projects and hinders practical learning by direct manipulation of the process and the working environment (similar effects have been observed in the software domain, see (Draxler, Jung, Boden, & Stevens, 2011)), and limits the possibilities for appropriation of the artifact in terms of the development of individualized practices from the side of the users.

Due to the variety of possibilities of a 3D printer, such as the printing of clothing, bakeware, but also more important prosthesis or even organs, our current society is getting more and more penetrated by such technologies. An important aim is therefore to enable all everyday users to adapt and appropriate the technology – like personal computers. But if such new techniques like 3D printers should have an impact for personal use – even for non-experienced laymen – the users need a deeper understanding of the used technology. For getting such a deeper understanding of how the machine works and more aware of what happens when and where and perhaps why, the users must appropriate the 3D printer – otherwise there will always be just a professional elite utilizing digital fabrication (Moilanen & Vadén, 2013). In order to achieve such a broader impact and develop a private collective innovative ecology (Troxler, 2010), we hence suggest extending the work that has been conducted in the field of supporting appropriation of software tools – for instance in the sense of providing infrastructures that support appropriation (Pipek, 2005) and making technologies "sociable" – to the hardware domain. The three dimensions we have outlined above present a first approach into that direction and we already derived design implications for designing first types of "Sociable Technologies" (Ludwig, Stickel, Boden, & Pipek, 2014).

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