Towards Sociable Technologies: An Empirical Study on Designing Appropriation Infrastructures for 3D Printing

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ABSTRACT

Over the last years, digital fabrication technologies such as 3D printers have become more and more common at universities and small businesses as well as in communities of hobbyist makers. The high complexity of such technologies, the rapid technological progress and the close link between hardware and software in this field poses challenges for users and communities learning how to operate these machines, especially in the contexts of existing (and changing) practices. We present an empirical study on the appropriation of 3D printers in two different communities and derive design implications and challenges for building appropriation infrastructures to help users face those challenges and making technologies more sociable.

Author Keywords

Appropriation infrastructure; sociable technologies; infrastructuring; empirical study; user-centered design; 3D printing; hardware-related context.

ACM Classification Keywords

H.5.3. Group and Organization Interfaces

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, printing and finishing professional artifacts and prototypes. Over the last years, entry level 3D printers and machines such as RepRaps or MakerBots have become more and more common in various professional and non-professional settings such as universities and small businesses as well as in the hobbyist and semi-professional Maker scene. A 3D printing process in a Maker setting usually starts by either constructing a 3D model via CAD software or downloading and maybe customizing one from specialized and usually open source sharing platforms from the internet. The model is then fed into the printing software running on a computer which generates tool paths for the print head. This path is then uploaded to the printer and the printing process is imitated after the printer has been pre-heated and calibrated.

3D printers are based on rather new materials and technologies that make it difficult to adapt established use concepts from existing IT ecologies like desktop software, mobile devices or '2D' printers. In traditional settings, users have found ways to 'socialize' these technologies, but handling contemporary 3D printers cannot be compared to the "plug-and-play" operation of common computer hardware. Particularly, hardware breakdowns, unexpected effects concerning the printing material, unintuitive modeling tools and complex configurations make the handling finicky and difficult to understand. Furthermore, rapid technical progress and the close link between hard- and software as well as the different printing technologies pose challenges for the users that are difficult to meet with existing supportive tools. Therefore, tools are needed that enable users to keep up with the fast development and deal with the complexity of the technology [28].

Moreover, users often discover ways of using technologies that were not anticipated by the designers and manufactures of the machines by trying to make sense of sophisticated 'new' technologies in the context of existing (and changing) practices [6]. There is an ongoing discourse in HCI by researchers studying appropriation and related activities as well as how to design support for these activities [11,24]. However, such studies and concepts usually address software ecologies, while an interest in how users appropriate digital fabrication technologies for 'making', what challenges they encounter and what useful practices they have developed in their daily use in more material, highly hardware-related ecologies needs to focus on physical-material issues to develop appropriation support/infrastructuring approaches here.

Based on an empirical study in two different communities, this paper aims at illustrating existing practices and technical approaches of 3D printer users appropriating these technologies for their purposes. We developed our study concepts from previous research on supporting the appropriation of software products, namely *appropriation infrastructures* and *infrastructuring* and show what design issues arise in order to extend them to the hardware domain

DIS 2014, June 21–25, 2014, Vancouver, BC, Canada.

ACM 978-1-4503-2902-6/14/06...$15.00.
http://dx.doi.org/10.1145/2598510.2598528

to provide what we like to call *sociable technologies* with an integrated appropriation infrastructure.

RELATED WORK

Research indicates that digital fabrication technologies significantly influence and change the landscape of personal device fabrication [20]. 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, spanning from DIY biology [16] up to the fabrication of complex personal electronic devices [20]. Some experts assume that in the future, digital fabrication technologies might be available in every household [37]. There are, however, many obstacles to overcome in order to approach this level of prevalence: The rapid advancements in those complex technologies [13] and their swiftly growing presence in new domains like those of hobbyists [34] are seen to warrant or even necessitate corresponding advances in interfaces and other tools to support the usage and especially the appropriation of these new technologies [1,29,36]. We base our research on two discourses, the one on *(IT) infrastructures* and the one on *appropriation,* both considered in a specific (*hardware-oriented*) context.

We base our understanding of *infrastructure* on Star and Ruhleder [32] which focuses on a socio-technical relation between a technological system and the use dependencies that are established through practices that rely on them. Infrastructures are understood as running below other structures, are embedded in social and technological structures, encompass taken-for-granted artifacts and use arrangements learned as part of a community membership, are shaped by and shape conventions of practice and are usually invisible (they become visible in breakdown situations). The importance of an 'user network', i.e. considering the social part of the socio-technological system is emphasized [32]. Inspired through this perspective, processes of infrastructuring surface that connect 'global' infrastructures to their 'local' usages, the appropriation of an infrastructure becomes part of designing it and its usage. Concepts to analyze and design support for 'infrastructuring activities' ("all activities that contribute to the successful establishment of an infrastructure usage") complement other user-oriented, user-centered or participatory design methodologies [e.g. 29] by practice-driven approaches that radically focus on the established usage, not the completed technological artifact as the focal point of design. [14,23]. Other approaches focus on the connection of infrastructures and social systems like practice communities [14,23] or publics [7].

Following Pipek [25], *appropriation* is the discovery and sense making of an artifact (like a new IS) while using it in practice. This understanding has its roots in established CSCW and 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 [2,8,18,33]. The concept of appropriation goes deeper than that of customization or tailoring of software in that it can encompass fundamental changes in practice and embraces the possibility of users adopting and using the technology in ways not anticipated by its designer [25]. Furthermore, it has to be noted that appropriation is associated with processes of exchange and interaction in networks of co-users where experiences and stories are shared between actors involved in the appropriation process [12,18,22,25]. 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 [15,34].

Pipek focused on developing appropriation support functionalities for connecting users of one tool, while Stevens et al. [23,25] looked at ensembles of tools and suggested an appropriation framework that would also address the developers interest in improving the technology. Aside from the core features of an interactive system (e.g. a CAD tool, an IDE or a printer), this framework adds second-level-functionality to support all associated appropriation activities. Examples for appropriation frameworks for software centered domains include the development and integration of a participative feedback tool into the Eclipse IDE [9,10] or attempts at formalizing a theoretical appropriation model focused on software [4]. The integration of appropriation frameworks directly in the IS which it is intended to support has been thoroughly investigated, tested and seems to have merit [25,33,38]. Traditionally, if hardware was involved in such studies, it is mostly considered in a systemic way in conjunction with software [6,19]. Generally speaking, this makes sense since complex hardware usually also has software components, but given the discrepancy in scope between the scientific work regarding software vs. hardware appropriation, we believe it is necessary to focus on hardware aspects in order to bring the regarding both sides to an even synthesis.

The connection of technologies and their user communities also requires a consideration of design issues for community technologies. The *Sociability* of technologies has also been discussed in HCI e.g. with regard to social media. According to Preece [27], online communities with good sociability have social policies that support the community's purpose and are understandable, socially acceptable, and practical. This includes as a technological design aspect a good usability, in particular with regard to registration issues, trust, security and governance issues [17]. To ensure participation in a community, Preece and Shneiderman [26] described design concerns with regard to 'reading' (attraction/motivation to revisit the online community), 'contributing' (attraction/ motivation to post, change or comment content), and 'collaborating' (attraction/motivation to react to other users actions and engage in shared projects). Bouman et al. [5] suggested to

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

design interactions that mimic 'real' interactions, that help building an identity, that help to actualize oneself, and, most important, that enable existing or envisioned practices of the intended target audience.

The idea of sociability *towards* technology has been brought in the spotlight through Byron & Nass [28] who argue that people respond in a social way to technology, treating it similarly to other human beings. Barraquand [3] builds on this notion but argues that true sociable technologies need to facilitate sociability *through* technology. He tries to foster this by building a framework for sociable technologies that is rooted in psychological considerations and emphasizes the importance of collaboration and context information. Norman [21] connects the notion of sociable technologies with supporting communication, team work, and troubleshooting the technology with an appropriate appearance which, for him, means careful design with cultural and social factors of the technology's field of application in mind.

We want to base our understanding of sociable technologies on these approaches, and derive from the necessity of building appropriation infrastructures that incorporate sociability into technology that we need more design-related studies and concepts which connect (online) community interactions, material foundations (in terms of materials and devices/technologies used in practices) and the emergence of practices themselves. Based on the approaches we discussed here, we analyze the practice of 3D printing for activities of infrastructuring, i.e. individual, communicative or collaborative activities aiming to change technologies, conventions or usages once a practice has been interrupted either by a breakdown or by a new idea to use a technology. We look for patterns of appropriation and try to understand what would make the technologies sociable. Using a qualitative approach, we aimed to capture data that is highly infused with in-situ and contextual aspects and allowed for thick descriptions and understanding as well as associate those insights with designing sociable technologies [3,21].

RESEARCH APPROACH AND METHODOLOGY

In order to better understand how IT can support appropriation work and the facilitation of sociable technologies in hardware centered settings and how user networks in such contexts are built up, we first have to understand the current usages of the hardware. In our study we focus on 3D printers as the specific hardware domain, covering the entire usage from the 3D modeling, the printing itself and the finishing of artifacts or prototypes. Since entry-level 3D printers are currently not very common in private households, we focus on research and Maker settings (as opposed to professional staff working in digital fabrication). We conducted a comparative study in two different 3D printing communities. The first community is one of Human Computer Interaction researchers at a German University (HCI-UNI). Here, two Fused Deposition Molding (FDM) printers (MakerBot and MakerBot 2X) and one full color powder composite printer (ZPrinter) are available. These are located centrally in the so called HCI-Laboratory (Figure 1, left) together with other workshop tools. The HCI-Laboratory is also used for team meetings or project groups and is frequented openly by students too. This paper mainly concerns projects related to the FDM-printers since the ZPrinter is a professional tool (and orders of magnitude more expensive) which is employed mainly for specific complex projects and hardly for non- or semiprofessional use. The second community is one of artists at a German Academia of Media Arts (HCI-ART). They have just one FDM printer (MakerBot 2). It is located in an outbuilding, which is mainly attended for printing purposes (Figure 1, middle and right).

The view on the field was sensitized by our design intention. We conducted a Grounded Theory oriented approach [32], 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 by bringing together those actors of the communities which already handle 3D printing and giving them an opportunity for discussing current practices and problems.

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 was separated into three parts: 1. The participant's work context, qualification and work steps with the 3D printers. 2. Entry obstacles, problems and their articulation. 3. 3D modeling, tools and related problems. The questions as well as the structure of the interviews were derived from the previous fieldwork (workshops and observations). All interviews were recorded and transcribed for later 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 (Post-Doc)	HCI-ART

Table 1: Interview participants

RESULTS: CURRENT PRACTICES OF 3D PRINTING

From playful first steps to semi-professional 3D Printing

Unlike normal printers or office tools, which are used only for practical reasons, the printing with 3D printers evokes a certain fascination for the users and interested people.

"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)

The curiosity and above all the private playful interests are the main motivational factors for dealing with such novel machines (I02). So, at first it was all about private artifacts such as a camera cover (I01), testing the functionality of printing a Minecraft landscape (I02) or the printing of jacket holder [hooks} for the office (I03).

"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 [printer] and also started to deal with 3D modeling, how it all works [...], how to clean it, maintain it and what to do when it will not work" (I02)

Shortly after the acquirement of the Zprinter, there was an official introduction within the group, in which a representative of the printer manufacturer explained the printer and its handling. After the representative left, for half a year nothing was printed. After this period, nobody really remembered how to use the printer (I01). Thus, the initial printing projects were a *"constant mix of experimenting and watching tutorials"* (I01). True to the motto 'The proof is in the pudding' most people read little literature before printing, but exchanged ideas and experiences directly with colleagues and started printing simple models (I03).

"As I see it, appropriation is most sustainable, if you just print and print. You can be productive very fast, because the learning curve is very flat. But for me, each print is still appropriation once more." (I03)

A provisional appropriation of printer-specific settings, especially if it is not a DIY-printer is that difficult as there are only a few specifications that you have to set (I04).

"The real problem is then to experiment with the specification values for the different materials, to find the optimum value, look at how fast you can let the extruder run, because less speed leads to more precision and if you have a large model, then the printer runs perhaps the whole day, which you might want to avoid." (I04)

All interviewees share the opinion concerning appropriation of a 3D printer or any hardware, that the concept 'learning by doing' is very important. Hence, it is seen as necessary that in the run-up to 3D printing, the uncertainty of the people to break something must be reduced (I04).

"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).

In contrast to the "The proof is in the pudding"-concept for the actual printing of a model, during the creation process of 3D models, significantly more literature research is done, but it is still a mix of testing and research.

"I have already clicked through bulletin boards for a long time, because first you have to know how to create a file, what should I take care of in order to build these STLs [Surface Tesselation Language]. It has almost taken two or three months until I got the results I had imagined or rather that I could imagine what the end result would be." (I06)

In addition to special community forums, of course Google is used as a primary source for finding information. To allow for easier introduction to the modeling, HCI-ART provides a basic seminar for their students on this topic (I05), in which participants are trained to design simple 3D models and avoid 3D printing related modeling problems.

Context-dependent Problem Recognition is a Problem

It is unavoidable that problems occur during the entire 3D printing process consisting of the previous modelling, the printing itself and the necessary post-processing. However, such problems trigger meta problems in that identification, understanding and locating the issue poses big challenges:

"I think problems are rather that you first have to find out what the problem is and of course, you can then google it with keywords like "it [material] jerks through the printer somehow" or something. But first you have to figure out that for example you need a new plunger or that the problem is connected to this plunger." (I02)

If you print with 3D printers, which a construct consisting of hardware as well as software components, a problem cannot be always traced directly to one of these components and it possibly arises only through specific, situated interactions or constellations of both components:

"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)

In addition to software and hardware as possible error sources, another component is crucial, which can decide the success or failure of a 3D print: Namely, the physical conditions and environmental context play an important role. For example: While trying to solve a different problem, a user encountered by accident that an open window causes the material to cool too fast and warp:

"It just takes a long time to figure out something like this. 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)

Beside the breeze from the open windows, which result in uneven cooling of the print, the general temperature of the room is an example for another important environmental context factor with a similar effect on the print:

„So, temperature is always a problem concerning the plastic printer. Whether it is winter now and inside the room there are 20 degrees or because the heating is on or the sun shines directly on the model and you print in black ABS plastic. That makes a big difference." (I02)

Hence, a problem cannot be easily identified and specified, because a number of other factors which often are not obvious and consequently not considered. In this, 3D printing differs e.g. from writing program code and the specific exceptions thrown by a compiler. However, to report and discuss a problem, it is essential to capture all those possibly influential factors in order to frame the problem in accordance with its overall context (I02).

„It would not help the people when I say: "I wanted to print something today and had the following error message". This won't help anyone. I would have to say to them, I printed with the powder printer [Zprinter] and maybe there were such and such specifics in the model or something. All those things like that… All that could be important to solve the problem, but you often do not know exactly what it could be." (I01)

If a problem is identified reasonably as such, it can be very difficult to find a solution for it or even to search for it because the difficulty of capturing and phrasing a question in a context-oriented manner is mentioned as a major problem (I02). A further problem akin to this one is that in the hacker and maker community a domain-specific culture with a corresponding and evolved terminology and vocabulary is prevalent:

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

The Process towards a Problem Solution is at least as important as the Solution itself

Both the community of the Chair as well as the Academy of Media Arts does not use their printers very frequently, so problems with routine and the retention of experience arise.

"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)

Especially the printer-specific settings are forgotten repeatedly (I04) which makes it necessary to preserve such data. To facilitate the first steps into 3D printing and the use of the printer, some measures have been already taken. A poster was printed and hung up close to the printer, which visualizes important information about the printing process.

"It was about a poster for presenting some best practices and providing an introduction to those people that might be interested in 3D printing: Especially the basic settings and tips. How can I start with the modeling of 3D models and what is Thingiverse and so on." (I04)

A problem with this, however, is that there is no one single standard process to achieve the printing goal. Especially the many contextual print- or model-specific problems cannot be anticipated in advance and thus externalized.

"It is not that easy to devise a standard process and document it somehow that a person who has no idea may reproduce it easily because the machine is in my opinion bit too complicated." (I02)

For this reason it is important to register how a user achieves a result. The steps and processes to a finished 3D print and its problems which have emerged must be described comprehensive and documentation cannot only focus on and present the final result. Otherwise the whole process cannot adequately be reproduced.

"It would be nice to get an understanding of the whole learning process. This means not only getting the final results without all the discussions and developments that have resulted in it." (I04)

To foster collaborative learning processes, group 1 has set up a special blog where users can document and discuss experiences and issues regarding the 3D printer itself, the process of printing, as well as problems, obstacles and opportunities (I03). The blog is, however, only very rarely used, because its content has to be written after doing a print when the necessary specifications and settings are often already forgotten.

„The platform [blog] is not really appropriate for that because you have right now a model in front of you and run into an error or functionality does not work and you really want to solve the specific problem on time and then print the model. I do not want to write something on the blog in this situation somehow." (I01)

A wiki is considered as critical as well, because it must be allowed to have discussion on the process, to ask how exactly a context was like, to know exactly what was the issue and to be able to coordinate later you when need it (I04). When errors occur, right now the user is often left alone during the usage. If colleagues are near the printer, they are often addressed directly via the grapevine (I02). However, the appropriate personnel are usually not constantly available in such a heterogeneous and temporally flexible working field as a university.

It would help the users to have more precise information about the actual printing process in order to understand better their own way of working with the machine:

„I think there is a lot that could happen with the software for 3D printers, at least with those we work with, so we could see better where support [note: printed structures to prop up overhangs] is needed and how the printing process is actually executed." (I05)

Problems with Sharing of Knowledge and Experiences

Considering knowledge sharing, first the domain of knowledge must be defined precisely, because knowledge can either be found on the modeling, the actual printing or the entire process.

"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." (I03)

Internally, printer-specific settings, problems and practices are shared rather than modelling or process concerns. For aspects of modeling, primarily external services are used. Solutions such as Thingiverse offer good opportunities to see other models or to disseminate its own model, but also to have it examined externally:

"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." (I02)

An interesting thing about platforms such as Thingiverse is especially that in addition to the models which are printable directly, also various settings and best practices regarding the printing process can be listed and discussed:

"For each model you want to upload, there is a description. Then there is the model itself, which you can even look at a 3D model viewer and turn. There are photos that can be set, perhaps from a finished print or any exported images from the CAD software. But you can also write some text to it and say "this is that part and that is like this and that can be use like this". Then there is a second tab which is labeled Introductions. I think that's very helpful, the parameters are always relative to the individual printing." (I03)

This is, however, not mandatory in any way and if it is listed, it is done so in quite dissimilar manners as there is no real standardization in place.

"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)

It has to be said, that the validation or examination on Thingiverse does not always correspondent to rigorous standards and that there is no technical failsafe or screening for corrupt models like non-manifold ones, i.e. models with errors in their outer shell resulting in misprints, even if the errors cannot be spotted by the unaided eye.

"First, it looks very nice, but then you produce a lot of garbage, because after you have printed it, you realize – especially for functional objects – that they are designed badly or that they will not yet work as you thought." (I05)

Summary of Empirical Findings

The empirical study shows that both groups started 3D printing mostly motivated through private interests or playful motivations. Such playful motivations are very common in actions dealing with materiality, like working modifying wood or baking pastry dough. During those ludic steps towards 3D printing, much experimenting outweighs the study of literature that only happens occasionally. This is why the understanding of the printers is mostly limited to operational handling. Those difficulties in understanding compound the identifying, locating and fixing problems encountered in the printing process e.g. matching them conceptually to hardware, software or external factors. Solutions are sought both internally and externally. Internally, face-to-face conversations with colleagues are preferred. Attempts at preserving the knowledge resulted in a collaborative blog in HCI-UNI, which is maintained and read only very irregularly. This is because the entries have to be made by hand after a print and are therefore out of context.

No.	Empirical Findings	Challenges and Design Implications
	Current practices and usage behaviors during 3D printing	
1	The 3D printer itself is a black box for the users and lacks in methods to see and grasp how it really works	Sensor based capturing and visualizing of context and printer information to support a better understanding of the machine
2	General orientation of learning-by-doing and experimenting instead of an extensive literature research	Context-related ambient learning through software- and sensor-based hints / tutorials / best practices
3	Identifying and locating problems is an itself due to the high context-dependence of those problems	Sensor based capturing of environmental variables and mapping them to possible printing problems. Detailed visual presentation
4	The entire 3D printing process is very time-consuming because the users must always be close to the printer	Providing web-based and in-situ options for monitoring and managing the printer as well as communicating with it remotely
	Documentation and knowledge sharing	
5	The printer settings with regard to the model, material and individual print are forgotten regularly	Integrated print history with printer settings, material data, errors, etc. Recommendations for current prints based on the history
6	Individual documentation and sharing of 3D printing experiences is very cumbersome and involves multiple systems which keeps users from doing it	Print history from 5. should be presented to the user together with easy to use tools to add more information
7	Difficulties in asking for help because often, not enough contextual information can be provided.	Data from steps 5 and 6 should easily be postable to 3D Printing communities and social networks
8	Knowledge, tips and hints in sharing communities are scattered and not really searchable / indexed	Establishing an orderly, searchable data structure (format) for the data from the previous steps
9	Community-specific terminology hampers appropriation	Community-maintained dictionary and automated “translator”
10	Technical validation (manifoldness, etc.) has to be done manually by the users and is not standardized.	Integrated validation tool checking model specifications and matching them to the printer’s characteristics.

Table 2: Empirical Study-based Design Challenges and Implications

In HCI-ART, a basic seminar was established to provide students with a theoretical and practical introduction to the 3D printing process. In addition to the internal practices, the users often search for problem solutions in bulletin boards and follow discussions on the web. This search however, poses a problem in itself, concerning the domain specific slang and wording. On platforms such as Thingiverse or similar websites, 3D models themselves are central rather than solution processes and best practices (which crop up occasionally and spread out). This helps the users at times, but it does not support the appropriation of 3D printers and its entire process - they are faced with similar problems during next prints again and try to identify the problems.

DISCUSSION: SUPPORTING APPROPRIATION WORK IN HIGHLY HARDWARE-RELATED CONTEXTS

Based on the findings of our empirical study, Table 2 shows the emergent design challenges, from which we derived technical implications for supporting infrastructuring activities with an appropriation infrastructure and to make 3D printers more sociable. In general, our findings support the relevance of findings from the literature regarding the design of sociable technologies [3] and previously identified challenges in designing appropriation infrastructures [33]. In the following sections we will further investigate these issues with regards to the practices and the 3D printing related context. The numbers in the discussion correspond to the numbering in Table 2.

Practices and Usage Behaviors in 3D Printing

1. A serious shortcoming that became apparent is that the 3D printer itself is a kind of lack box for the users and lacks in methods or functionality to visualize how it works. In order to overcome this issue, we suggest providing users with more details about the current printing process. Providing the right kind of information allows them to get a deeper understanding of how the machine works and the users can become more aware of what happens when and where. By adding new sensors into the machine itself and leveraging the built-in ones, new ways of capturing and monitoring the status of the machinery and detailed information about the printing process can be made available. Our study indicates for example that users could benefit from being provided with current printer data such as temperatures (e.g. print bed and the printed object itself) and their development over time, extruder movement and acceleration or more detailed simulations and progress information of a print. A visualization dashboard could be web-based and should be available in-situ, integrated into the machine, e.g. on a big, high-resolution display as opposed to the currently used small LCD screens which cannot display enough information as well as remotely.

2. The general orientation of learning-by-doing and experimenting outweighed extensive reading of user manuals or background literature. The users therefore often have just a vague understanding of the printer’s capabilities, functionalities and all kinds of problems arise – especially at the beginning of their printing career. Our findings

suggest that users should be provided with context-related ambient learning options for mixing their attitude towards experimenting with more profound understanding of the functionalities. For a better support of this mix of experimenting and formal learning, integrated software- as well as sensor-based hints, best practices and on-hand tutorials for each printing step should be provided. As an example: The calibration of a printer should not only be treated in short, concise instructions (as is often the case today) but background information for the reasons behind the process as well as its implications should be provided in situ (again, possibly on a big, integrated display).

3. If a problem arises, not only the missing theoretical background complicates the users' understanding and location of the issue: Due to the strong dependence of the entire printing process to its context and environment (e.g. uneven cooling and hence warping of a print resulting from a breeze through an open window), the user should be provided with much more detailed information about these variables to get a better understanding of their influence. By adding new sensors to the environment such as measuring room temperature and ventilation as well as mapping to the available printing materials, one might help alleviate those issues. This information should be displayed, again with the option for more in-depth explanation.

4. Time-consumption and convenience are an issue because in most cases, only the printer or the connected computer controls the printing process which means that the user should stay close to monitor or intervene. Remote monitoring (video feed and status updates from the printer itself) and especially control functionalities (possibly web-based and tied in to the dashboard mentioned above) are needed to solve this issue. Some of the very latest 3D printers (not available at the time of our study) already incorporate some of those features.

5. Print settings with regard to the characteristics of a specific model and the material are quickly forgotten after printing. To overcome this obstacle, the printer could integrate functionalities for saving a print history that includes all relevant data (model, size, material, printer settings, etc.) which are captured automatically. When a new user creates a new project, the 3D printer could then compare the user's project with stored printing specifications and offer in-situ settings advice.

Documentation and Knowledge Sharing

6. Closely related to the effect of forgetting printer specifications and settings, our study showed that the documentation and sharing of the printing experiences is very cumbersome right now because it happens out of context and temporally displaced. The data from 5. should hence be made available to the user directly after and possibly even during the print and he should be given the opportunity enhance and deepen it with his own experiences (in textual or visual form). To map the data to the user, a log-in mechanism (possibly integrated into the printer via NFC or similar technologies) would be needed.

7. Documentation and sharing is also important for asking for help under provision of all relevant contextual information, getting support and to distribute knowledge and experience to other 3D printer operators (hence, also for community-building). Accordingly, the information gathered in 5. and enhanced in 6. should be easy to send or post to social networks and communities (Thingiverse, Facebook, etc.) where they can reach the appropriate audience and discourse and help can be initiated. One might think of this process as distantly related to that of bug tracking tools. A corresponding API to receive the information on those platforms would be needed.

8. To enable step 7. in a structured manner, we need a standardized, indexed and especially searchable data structure for the enriched information which can then be used in the printer, the dashboard and the APIs in the social networks and communities. This structure needs to provide space for the inclusion of (automated) sensor data like the temperature or print timelines but also needs to place equal importance on the inclusion of "soft" data like individual experiences or workarounds which are invaluable for leaning, but very hard to share or find right now.

9. Not only the missing structuring of data impedes the searching process for help and the sharing, but the highly community-specific terminology (e.g. "warping") hampers this process. A community maintained open "dictionary", as well as an automated translator matching errors to this dictionary could help alleviate this issue.

10. Certain specifications like (un-)broken surfaces of models or overhangs can influence the print quality or the printability of a model itself. Those aspects currently are not checked or validated in 3D printers, printing software or the online sharing communities. This has to be done by the user manually which hampers appropriation, confuses users and has negative consequences for sharing and documentation. An automated validation system, built into the printer (or, more realistically into the controlling computer due to available computing power) could significantly improve those problems.

CONCLUSION: INFRASTRUCTURING AND SOCIABLE TECHNOLOGIES

In this paper we were able to uncover a lot of different problems and practices to cope with challenges of appropriating 3D printers in two semi-professional communities. Unlike traditional "plug-and-play"-printers from the "2D world", there is few previous practice users can relate to. Unexpected errors and breakdowns as well as complex configurations lead to difficulties in understanding and appropriating these machines for existing practices of 'making' and art production. We pointed out some design ideas for functionalities supporting these infrastructuring activities. They build on previous work for software infrastructures [6,10,18,27], but the physical/material conditions in relation to machine, printing material and artifacts also suggest to enhance those concepts with additional sensors and visualizations of printing processes, printers' environments and tasks/structures/workflows the printing is embedded in as well as by incorporating in-situ and remote tools for those purposes. We also found evidence for infrastructuring activities in the sense that the users modified their machines (e.g. installation of cameras) in ways the manufacturers did not plan for but could be incorporated in future generations of their machines.

Most of the infrastructuring activities were communicative or collaborative activities involving not only technology manipulations and combinations of various kinds, but also articulations of usages or breakdowns that referred to the technologies at hand and their context. Studies on these kinds of communications are not new (most notable example cf. 35), but current practices deserve a second look as the practices of communication change with the communication infrastructures users evolve along the developments of miniaturization, mobile and ubiquitous computing. The step we argue for now is to use this ubiquitous interconnectedness of devices to make more technologies 'sociable', meaning that the support that users now find outside the technology at hand in the Internet in general, in community forums or in neighboring offices should be integrated into the technologies themselves. Conceptually, these activities have been described as 'appropriation activities' if they consist of user-user interactions, or as 'infrastructuring' activities if they also relate to other actors of technology production and use or the further development of technologies and their foundations. A functionality to support all these practices within the existing infrastructure needs to address not only interoperability issues as they are addressed e.g. by defining standardized interfaces between different infrastructural layers, but also it needs to allow for and actively support the negotiation of socio-material aspects of emerging new practices connected to these technologies. Our studies showed that the ability to articulate and discuss use and configuration issues would benefit from 'Sociable Technologies' that describe themselves on three context levels, potentially using additional sensors, and providing visualizations and tools in three dimensions:

1) Internal context: Providing information about their inner workings about their current state as well as about their component and behavioral structure,
2) Socio-material context; e.g. location and surroundings, environmental data like room temperature, maintenance or user/usage data), and
3) Task/process context: e.g. technologies used to build/prepare printed models, position in a production chain or process, purpose and goal of machine usage.

In addition, they should include an integrated social network of their users (possibly also including stakeholders responsible for machinery maintenance/development) that allows for communication about practices, problems as well as possible solutions in various self-managing communities. To support that, the models and visualization describing the context layers should be easy to communicate and annotate. They may be even navigational structures e.g. one could fly through a virtual model of a 3D printer to the printing head to navigate to documentations and discussions with regard to that machine part. With regard to our example of 3D printers it becomes apparent, that particularly the integration of these 'social interface' functionalities into the device itself is crucial. Many of the aspects described are already communicated in existing infrastructuring activities, and e.g. with Thingiverse there is already a kind of self-managing online community, but media breaks, terminology issues and a lack of understanding where to ask for information make these solutions difficult to follow.

Based on the design issues described here, we are currently developing such a hardware-integrated appropriation infrastructure based on sensor-captured and visualized data of the entire 3D printing process. Evaluating this approach will give us a deeper insight to integrate the negotiation of usages into the devices we build, and bring us from an 'Internet of Things' to an 'Internet of Practices'.

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