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On the viability of the Open Source Development model for the design of physical objects

Lessons learned from the RepRap project

Thesis for the degree of
Master of Science
by
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Abstract

While open source software development has been studied extensively, relatively little is known about the viability of the same development model for a physical object's design. This thesis addresses this deficit by exploring the extent to which this model is viable for the development of physical objects. It starts with a review of the relevant literature on open source and user innovation communities followed by a case study and survey of the RepRap community.

This community develops a digital fabrication system that can 3D print a large share of its own parts. This allows for a decentralized community to independently produce physical parts based on digital designs that are shared via the internet. Apart from improving the device, dedicated infrastructure was developed by user innovators.

The survey reveals substantial adoption and development of 3D printer technology, comparable to the larger vendors in the industry. RepRap community members are spending between 145 and 182 full-time equivalents and have spent between 382,000 and 478,000 dollars on innovation alone. At the RepRap project's 6 month doubling interval, it is entirely feasible that its adoption and disruptive levels of innovation will exceed that of the incumbent industry. Within the community there is a higher incidence in modifications of hardware than in software, and, surprisingly, hardware modifications are expected to be relatively easier for others to replicate. The level of collaboration is also higher for hardware than for software.

Through Thingiverse, a web-based sharing platform originating from the RepRap project, 1,486 designs of physical objects in the last 6 months. Also, more than 10,000 objects were independently manufactured by its members' machines. While already substantial, this level activity exhibits similar exponential growth characteristics.

Many RepRap community members possess a fabrication capability that the average person does not have access to. While this does limit the present day generality of the case study findings, there are many reasons to expect a high likelihood of personal access to digital fabrication in the near future. The rapid development and adoption of increasingly affordable, yet more powerful and valuable fabrication technologies and the anti-rival logic of open design allow user-dominant collaborative development to have significant implications for the provisioning of goods in society.

Finally, I provide a discussion of the implications and make suggestions for further research.

Keywords: Open source development model, open design, user innovation, horizontal innovation networks, distributed innovation, flexible manufacturing.

Contents

Preface

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Chapter 1

Introduction

1.1 Motivation

Our information and communication infrastructures are evolving rapidly. As observed by Shapiro and Varian (1999), even if information is produced at a high fixed cost, it can be reproduced to high fidelity at negligible incremental cost. This hints at an enormous potential diffusion of valuable works. It stresses the importance of a better understanding of the provisioning and distribution of information based goods in society (Drahos, 2004). With the costs of communication falling, new forms of collaboration are emerging. One of these forms, called open source development, typically involves a large set of individuals and/or organizations sharing the workload (Haefliger et al., 2008) while the public good properties of the outcome are preserved (Bessen, 2005; von Hippel and von Krogh, 2006; Osterloh and Rota, 2007).

Open source software (OSS) development has attracted significant scholarly attention (Spaeth et al., 2008). A lot of research is devoted to explaining the characteristics of open source software development as being different from a traditional, more top-down development paradigm. The successes of projects like Linux, Apache and Firefox not only highlight the merit of the development methodology but also its real-world significance, robust functioning in the marketplace and its value creation potential (von Krogh and von Hippel, 2003). The non-exclusive nature of the output of the open source development process is associated with value spill-overs and at the same time enables organizations and individuals to innovate faster and at a lower cost (Lessig, 2001).

Studying the viability of the open source development methodology is specifically relevant because it has been shown to address several important issues concerning creation of public goods (Benkler, 2006, p. 119), and does so in a sustainable way in terms of continuity (Osterloh and Rota, 2007). Software and other information products can be considered non-rival, because distribution doesn't typically involve a loss of the sender. Distribution, because if its digital encoding, is virtually free.

In the literature, open source development of physical objects – so-called open design – is hardly touched upon. In open design, information such as schematics, bills of materials and assembly instructions are freely revealed. Prevalence of open source in physical design projects with some degree of visibility is still very modest when compared to software. Data collection on open design projects by Balka et al. (2009) resulted in 85 listed projects by August 2009, which is a relatively small number when compared to over 380,000 open source software projects on SourceForge in the same year[1].

When broadly defined, open design predates open source software by centuries (e.g. Allen, 1983; Nuvolari, 2004). Yet the distributed nature of open source development had not emerged in open design as it has in software. The low number of hardware related projects may lead observers to think that it is not a viable domain for open source development. By saying "electrons are cheap, but atoms are expensive" some have raised doubt whether this mode of development is viable (Ackermann, 2009, pp. 210–211).

Through an in-depth study of the RepRap project, in which both software and hardware development are present, this thesis will help remedy this knowledge deficit. We will investigate what influences the viability of this mode of development for physical designs.

The aim of the RepRap community is to develop a low-cost machine that can fabricate physical objects of arbitrary shape, including copies and improvements of its own parts. The fabricated objects are based on digital content and the owners of the RepRap machines can download, improve and redistribute designs via the internet, as well as fabricate physical instances of such objects. Like many larger open source software communities, but unlike most hardware based projects, the RepRap community is geographically distributed.

> Benkler (2006, p. 121) remarks that *"[t]he highly distributed capital structure of contemporary communications and computation systems is largely responsible for this increased salience of social sharing as a modality of economic production in that environment. By lowering the capital costs required for effective individual action, these technologies have allowed various provisioning problems to be structured in forms amenable to decentralized production based on social relations, rather than through markets or hierarchies."*

Benkler goes on to stress the need to reconsider the appropriateness of market-based firms as the primary modality of production in fields that are undergoing a technological transition that affects opportunities for a collaborative mode of production that is rooted in a culture of sharing. By studying the RepRap project, we evaluate a

[1]SourceForge is a popular open source project hosting solution. In February 2009 there were 380,000 projects listed. From: `http://sourceforge.net/about`

project suggesting upcoming technological change impacting the development of physical goods.

The high growth rate of the community and its surrounding ecosystem, the rapid diffusion of distributed production resources provide the primary means for distributed physical prototyping and production[2]. It is of high importance to investigate the implications of such availability of low-cost physical production resources and which role they play to extend social production beyond the virtual world.

1.2 Problem statement and research questions

Because the development model of open source software apparently can produce highly successful output, it is very important to see if, and how, this model can be applied to a wider range of provisioning problems. Weber (2004) also emphasizes the importance of this question, stating that *"[t]he open source process has generalizable characteristics, it is a generic production process, and it can and will spread to other kinds of production. The question becomes, are there knowledge domains that are structured similarly to the software problem?"* He goes on to say that: *"The key concepts of the argument – user-driven innovation that takes place in a parallel distributed setting, distinct forms and mechanisms of cooperative behavior regulated by norms and governance structures, and the economic logic of "antirival" goods that recasts the "problem" of free riding – are generic enough to suggest that software is not the only place where the open source process could flourish."* While others (e.g., Shirky, 2005; Nuvolari and Rullani, 2007) have suggested the generality of these aspects, few studies have been conducted that demonstrate how open source development can be applied to tangible items. By comparison, open source software development has been studied quite extensively for various reasons (Spaeth and von Krogh, 2007). The literature on user innovation communities includes many studies of highly distributed communities producing software[3]. It also includes studies of such communities developing and exchanging physical resources. Yet, the latter communities mostly lack the spatial distribution and frequent interactions that characterize many software projects. This appears to be a result of the logistics of physical objects and the resulting difficulties with communicating physically embodied knowledge[4]. Based on the existing studies, it's not evident whether this type distributed development is viable. This study of the RepRap project not only provides a strong indication

[2]Typically, the more mature open source software communities are accompanied by for-profit organization. This is common because of the value being generated by the ecosystem as a whole, allowing organization to capture some of it. Likewise, the RepRap community is encompassed by an ecosystem of user-founded businesses, manufacturing service providers and user innovators. Hybrid ecosystems having both user innovators and manufacturers have been studied by Shah and Tripsas (2007) and Baldwin et al. (2006). The dual role within a single organization is studied by Block et al. (2010).

[3]Crowston and Howison (2005) found that *"larger FLOSS teams tend to have more decentralized communication patterns". See also Lee and Cole (2003).*

[4]von Hippel (2001, p. 86) concludes that in contrast with open source software, innovation in equipment are embodied and distribution requires physical production and distribution and involves economies of scale. The result for physical products generally is that innovation can be carried out by users and within user communities, but production and diffusion of products incorporating those innovations is usually handled by manufacturing companies.

that it is viable, it also tries to identify those factors that influence viability and discusses the generality of these findings.

The stated problem will be addressed by answering the following research question:

To what extent is the open source development model also viable for the design of physical objects?

I will start addressing this question by referring to research that explains the viability of open collaborative innovation projects in general. This mode of development is not specific to software or physical products (von Hippel, 2005b). I will show that the conditions for viability are met for the specific case of the RepRap community. In the case description I will also show that, while the tangible dimension is relatively unique, RepRap has many things in common with typical OSS communities.

Question 0: What is open source?

Before addressing the actual research problem, we must first clarify our meaning for the term ”open source”. We will address this with a review of the current literature on open source in chapter 2. Afterwards, the two main research questions will be addressed. After having described what Open Source Software and open design have in common, the first research question focuses on differences between the two and their impact.

Question 1: What are differences between open source software development and open development of physical objects?

This question will first be addressed from a primarily theoretical perspective. To further explore these differences the creation, transfer and diffusion of innovations in each area will be compared statistically through the survey.

Question 2: How are drawbacks of the physical nature of open design addressed in the RepRap project?

Because frequent exchanges of physical innovation are common among members of the RepRap community, these will be qualitatively examined. In particular, we will identify resources and cultural factors that facilitate these interactions. Resources include knowledge, infrastructural tools, software tools and physical equipment. Cultural aspects concern norms and rules present in the community and the way in which feedback and appreciation is given. The case study will reveal how tools and culture, taken together, enable distributed physical prototyping. The statistics from the study reveal to what extent the drawbacks in hardware’s physical embodiedness are mitigated in the RepRap project.

1.3 Methodology

For any detailed comparison between the way in which open source software and hardware are developed, it is valuable to adopt a theoretical perspective that generalizes features unique to either of the models. Through the literature review, two theoretical perspectives are found to be appropriate. These perspectives will be evaluated in the literature review. The context for addressing the research problem will be provided by both the literature on open source software and the more general research models applicable to open source innovation. I will draw from the latter research models because they have proven to be applicable to software development without being limited to software alone. They have frequently been used to study collaborative development of physical products as well.

To confine the areas in which to find differences, we look into a single community which develops both software and hardware to solve a common problem. The emphasis is not on differences between distinct open source software and open design communities. For an overview of various open design communities and their differences see Balka et al. (2009).

Using a single community benefits this research by limiting variation with regard to the product, producers and many other parameters of the community. The RepRap project's main product is a functional design of a machine employing both software and hardware. Differences resulting from whether product innovations pertain to a software module or to a physical part become more salient when most other parameters are constrained.

1.3.1 Case study

To understand how open source development can function outside of the more familiar context, a case study helps answer the how's and why's (Lather, 1992; Robottom and Hart, 1993; Ellis and Levy, 2008; Yin, 2002). In this case it will be used to better the understanding of participants' actions and the context of their behavior.

Since our interest is in understanding something more general than the case, adoption of an instrumental case study methodology is deemed appropriate. The case, as an instance of the studied phenomenon, plays merely a supportive role toward understanding the phenomenon. The case is looked at in depth, its context scrutinized, its ordinary activities detailed, and to help the researcher pursue the external interest. The case may or may not be seen as typical of other cases. (Stake, 1995)

Because the choice between an instrumental or intrinsic case study is not obvious, it deserves some clarification. Stake (Ibid.) uses the term intrinsic, suggesting that researchers who have a genuine interest in the case should use this approach when the intent is to better understand the case. This should not be undertaken because the case represents other cases or because it illustrates a particular trait or problem, but because in all its particularity and ordinariness, the case itself is of interest. In an intrinsic case study, the purpose is not to understand some abstract construct or generic phenomenon (Baxter and Jack, 2008, pp. 548-549).

As mentioned in section 1.1 this thesis includes an in-depth examination of the RepRap project. The case is very interesting in itself for several reasons: the fact that open source development is practiced beyond its familiar scope, the physically embodied nature of the exchanged innovations[5], the frequency of these exchanges, the rapid growth of the community and, finally, the individual members' access to resources that even few firms have. On the face of it, the generality of the findings from such a case study seem to be very limited. After a more in depth review of the literature, however, it appears that the theory actually predicts the observed activity. Given the good fit with the already well-established body of literature, it seems a mistake to consider it as *sui generis*; an isolated case that does not fit into a broader encompassing framework. The fact that this particular case has properties that are salient does not imply that its properties are fundamentally new. Recent developments, however, allow a much larger group of individuals to participate in this extended scope of open source development.

1.3.2 Survey

Empirical data was gathered by administering a survey among users and developers in the community. The survey provides insight into adoption, creation, transfer and diffusion of both software and hardware innovations and the importance of location and infrastructure for diffusion of innovations. Under the conditions present in the RepRap community, there is a certain impact of tangibility of hardware (having to do with the embodiment and logistics, as we will later see). Empirical data is used to determine the nature and quantitative significance of these effects.

Participation in the survey was limited to only those who build and/or operate open source or open source derived 3D printers. This excludes a larger group of people who interact with the community but aren't building their own machines, but it allows more in depth questions pertaining to the adoption, use and modification of the machines. Invitations to participate were posted on various blogs, forums and social media platforms that community members frequently access.

1.4 Thesis outline

This thesis is structured as follows. The current chapter introduces the research problem and explains how it is addressed. Chapter 2 serves as the theoretical foundation by defining open source and by reviewing the relevant literature. Concepts most important to addressing the research problem at hand will be identified here. This chapter addresses research question 0, "What is open source?". The case study of the RepRap

[5]See Drahos (2004, p. 328) for an account on codification of knowledge relates to physical embodiment and on the public good qualities of such embodied information

community and its development process is provided in chapter 3. Chapter 4 will contain a qualitative analysis of the RepRap contributors to determine differences between software and hardware with respect to creation and diffusion of innovations, thereby answering research question 1. Then, in chapter 5, we will revisit the theoretical part and confront it with the empirical findings from this study. The empirical findings from the study, together with the analysis explore how the drawbacks of the physical nature of open design are addressed in the RepRap project (research question 2). Conclusions from this analysis will be drawn at the end of chapter 5. Finally, chapter 6 concludes this thesis with a discussion of the findings, their limitations, and provides suggestions for further research.

Chapter 2

Theory and literature review

For a proper analysis of the case, a good definition of concepts like open source, open source communities and projects is pertinent (covered by section 2.1). In addition, to meaningfully contribute to the existing body of literature, it needs to be clear how the case aligns with the existing theory and research perspectives (section 2.2).

2.1 Terminology and definitions

For this analysis it is important to clearly define what open source is. The term has several distinct but related meanings. It is used to denote a practice regarding the licensing of intellectual property of software and other creative works. In addition, it is often referred to as a development methodology and in some cases as a collaborative strategy between users and user-firms (Behlendorf, 1999). Moreover, open source is used to refer to communities where these collaborative strategies and the development methodology are being practiced (Gacek et al., 2002). This section elaborates on these meanings.

2.1.1 Defining open source

Formally, for software to be called open source its license must conform to the Open Source Definition (OSD) as outlined by the Open Source Initiative [1]. Most notably, the OSD implies that such software has a license that permits modification and must require free redistribution of the software under the same license. The licenses compatible with the OSD are mostly based in copyright law since this type of intellectual property law is most applicable to software, which is the area where free and open source practices emerged.

Perhaps the most important function of open source licenses is to ensure non-exclusive access to the intellectual property. This inverted application of intellectual property law has many implications. From the perspective of the individual developer,

[1] See `http://www.opensource.org/docs/osd` for a full copy of the OSD.

it helps to prevent appropriation of their work. Moreover, reuse and improvement of open sourced products can be carried out without needing to ask for permission. This reduces transaction costs, the barriers to contribute and duplication of effort. Moreover, potential benefits encourage a more modular approach, which is often considered a good development practice for maintaining high quality standards even for systems with a high complexity.

It should be noted that the current OSD does not lend itself well to also cover physical product licenses, as these may need to also draw on other legal domains. Copyright law can only be used to protect implementations of ideas, and not the ideas themselves. In this way, the license will apply to copies of design documents and design files, but the design itself is not copyrighted (Ackermann, 2009, p. 192). Moreover, the non-exclusive nature of the design files does not preclude the existence of patents that impose limitations on the use of the files for manufacturing the object, however the same could be said for software patents. It is difficult to assess the impact of interactions between these legal domains and it is further complicated by the fact that there are legal differences between the various different geographical regions. Most of these issues remain unresolved, though some new development are underway.

Recently, a version of an Open Source Hardware (OSHW) Definition was drafted[2]. It is, as yet, in an early and volatile state, borrowing mostly from the OSD. Some open source licenses pertaining to hardware have been developed, though none are very mature nor have they seen widespread adoption. Moreover, the lack of test litigation makes it unclear whether they will properly perform their function. Lacking maturity introduces the risk of appropriation, which in turn could reduce incentives to contribute.

2.1.2 Open source licenses

Current implementations of licenses conforming to the OSD vary mostly due to disagreements over how far downstream in the development process appropriation should be restricted. The most commonly applied license, the GPL[3], requires that all derivative and downstream modifications are released under the same license and may be distributed freely. Other licenses, such as the MIT and BSD licenses do not contain provisions preventing developers from creating derivative works without also making the source code available.

The differentiation of freedoms in the various licenses originated from the varying strategies of stakeholders of the licensed works. Some business model's value capturing components are based on selling a software product and thereby depend on exclusion of this product in the absence of a monetary compensation. Many other viable strategies exist, ranging from charging for the core while having open source

[2] The most recent version of the OSHW can be found here: `http://freedomdefined.org/OSHW`

[3] GNU General Public License, of which version 3 can currently be found at `http://www.gnu.org/licenses/gpl.html`.

extensions or vice versa, to charging for services and support or customization of the software. Apart from partly closed strategies, keeping it entirely open can also have significant strategic benefits. For example, it has been used to shift the locus of competition towards hardware[4]). In addition, it can take the friction out of business collaboration, develop social capital and reduce costs (Tapscott and Williams, 2008, p. 94). Moreover, if the functional relationship of the stakeholder is to benefit from the *use* of the software, an open approach may encourage others to improve the product. A user tends to freely reveal his innovations. User free revealing, however, is by no means limited to software, as we will further see in section 2.2.1.

While a comparison of the licenses is beyond the scope of this thesis, the better-known open hardware licenses include:

- The TAPR Open Hardware License (OHL): drafted by attorney John Ackermann, reviewed by OSS community leaders Bruce Perens and Eric S. Raymond, and discussed by hundreds of volunteers in an open community discussion.
- Balloon Open Hardware License: used by all projects in the Balloon Project.
- Hardware Design Public License: written by Graham Seaman, administrator of the website www.Opencollector.org.

2.1.3 Open source as a development methodology

The meaning of open source as a development methodology has been given thorough attention by scholars such as Raymond (1999), von Krogh and von Hippel (2003), von Hippel (2001) and Benkler (2002). However, it is important to note that the collaborative practices that are observed in open source development do not require a certified open source license. Several ways of freely revealing innovation outcomes would, at least to some degree, enable others to provided feedback, test and improve that work. These development patterns have been studied extensively and are so closely related to open source development that generalization is justified. Any description that covers more of what goes on in a typical open source community would have to acknowledge that legal tools are only a part of the norms and culture affecting the community's behavior (Benkler, 2006). In the case of open source development, these legal tools are just another mechanism used because of their good alignment with the practice of collaboration. Norms other than those that are legally binding can be effective at stimulating developers to share their work and enable others to build onward. Formal or informal, a community's norms and culture determine, to a large degree, the behavior of its participants. Benkler (2006, p. 110) notes that cultural norms in social exchange systems

[4]From Benkler (2006, p. 46): "IBM has described itself as investing more than a billion dollars in free software developers, hired programmers to help develop the Linux kernel and other free software; and donated patents to the Free Software Foundation. What this does for the firm is provide it with a better operating system for its server business – making the servers better, faster, more reliable, and therefore more valuable to consumers."

can be more efficient than the costly monitoring and enforcement commonly employed in market exchange systems. Reciprocity and a shared understanding of fairness can be potent social mechanisms, and these are commonly present in open source communities. The reuse of modules can be encouraged with legal or non-legal norms. Legal norms such as those provided in licensing allow reuse without asking for permission. Informal norms can encourage application of such licenses, or encourage the collaborative behaviors even in the absence of such licenses.

Raymond (1999) put forward the following claims that have become embraced by many as good development practice. He first writes that *"the best programs are written in response to a developer scratching his personal itch"*. He stresses that an important reason for high quality in open source is that people are passionate about what they are developing because it is personally meaningful to them and they autonomously decide to work it. What he doesn't mention – and which is a strong argument supporting his first claim – is that users have good access to context-of-use related knowledge. Given that this use-related knowledge is often very costly to transfer to producers, this gives them an advantage in creating better-suited products compared to producers (von Hippel, 1995). This would help explain the dominance of users as developers in open source projects (Gacek et al., 2002).

Secondly, he writes that *"good programmers know what to write, great programmers know what to rewrite and reuse."*. This refers to the reuse of work done by others, while in other area's radically deviating from it, helping developers to achieve their goals more effectively. Interestingly, he points out that in the Linux world it is more likely than anywhere else that you will find almost exactly what you need as a basis to start from. The emergence of a commons of components that developers can base their work on facilitates faster development and allows developers to focus more on their innovative contributions. Furthermore, code reuse is applied because developers want to integrate functionality quickly, because they want to write preferred code, because they operate under limited resources in terms of time and skills, and so they can mitigate development costs. Moreover, knowledge and code reuse has been found to be an integral part of open source development practice (Haefliger et al., 2008; Bollinger et al., 1999). Maccormack et al. (2008) provide the explanation that without a modular design, there is little hope that contributors can understand enough of a design to contribute to it, or develop new features and fix defects without affecting many other parts of the system. It is, thus, a key enabler of collaboration in open source projects.

Thirdly, Raymond coined "Linus' Law": *"Given enough eyeballs, all bugs are shallow."*. This refers to the notion of large communities increasing the likelihood that it includes someone who is perfectly suited for the job, that is, motivated and uniquely capable of solving that particular problem. More recently (Jeppesen and Lakhani, 2010) have found that diversity has been shown to have a significant positive impact on problem-solving effectiveness (see also, e.g., Boudreau et al., 2008). Moreover, the transparency of the product's inner workings through availability of the source code allows a bug to be traced right to the line of code causing it. Apart from software, other products can be codified and digitized. In subsequent chapters I will further explain why this is relevant. Digitization can allow another person, regardless of his location, to retrieve the product in a way suitable for studying it and developing an improvement. Such improvements can be transmitted back, all at very low communication costs. When all improvements have to be developed by a centralized authority, it is very hard to transmit all required information to solve the right problems and solve them in the right way. Moreover, in contrast to development of large amounts of improvements in-house, modifications provided by a large audience of external developers can still be curated by a relatively small group of people.

2.1.4 User innovation communities

A community can be described as *"a network of interpersonal ties that provide sociability, support, information, a sense of belonging and a social identity"* (Franke and Shah, 2003). Open source software is typically developed by user innovation communities, but they are by no means restricted to software (von Hippel, 2006, p. 103). The reasons for participating in a community vary between communities and also between individuals. In user innovation communities, it is typical that intellectual property is not used to prevent others from adopting innovations but rather in the opposite way. Copyright law is used to preserve freedoms to use, study, share and modify the work. The members' willingness to share information usually depends on the functional relationship they have to the object of innovation. If they are interested in benefitting from the *use* of the innovation, rather than selling it, they are more likely to freely reveal their innovations so that others will improve on it (von Hippel, 1988a). Such improvements can benefit the initial innovators. Another reason is that it is beneficial for innovators to attract others to their technological trajectory (Osterloh and Rota, 2007).

2.2 Literature review

There are several research perspectives applicable to open source development that are not limited to software development. We will introduce two of them that are valuable as a basis for this research. Next, we will explore the literature on motivations to participate.

2.2.1 User innovation

User innovation, by definition, is an innovation process in which users, as opposed to producers, are the focal actors. As such, networks of user innovators can innovate independently of producers. Such a network can flourish when (1) at least some users have sufficient incentive to innovate, (2) at least some users have an incentive to voluntarily reveal information sufficient to enable others to reproduce their innovations, and (3) user self-production can compete with commercial production and distribution. When all of these conditions hold, we speak of a "horizontal innovation network". When only the first two conditions hold, the innovation process itself still concentrates around users, yet manufacturers focus on their more favorable returns to scale. (von Hippel, 2007) These communities are by no means restricted to the development of information products like software. They also are active in the development of physical products, and in very similar ways (von Hippel, 2005a, p. 103).

Various researchers have documented the development of physical products by users and user communities. Examples include sports equipment (Lüthje et al., 2002; Franke and Shah, 2003; Lüthje and Herstatt, 2006; Shah, 2005), scientific instruments (von Hippel and Riggs, 1994; von Hippel, 1976), medical instruments (Lüthje, 2003) and industrial process equipment (von Hippel, 1988b) and products (von Hippel and Finkelstein, 1979; Herstatt and von Hippel, 1992; Nuvolari, 2004), Morrison et al. (2002), mass production of steel and the personal computer (Meyer, 2003). User innovation is a phenomenon of major significance in many industries. A recent study by von Hippel et al. (2010) measured the consumer product development activities of 1,173 UK consumers. Analysis showed that 6.2% of UK consumers innovated (excluding innovations as part of their job), in aggregate spending 2.3 times more than the total expenditure of consumer product R&D of all firms in the UK, the majority of which were physical products and 14% involved software.

While user innovation is rooted in innovation management and industrial organization it does not fall into the trap of equating self-interest with pecuniary interest. It explicitly allows for a range of motivations to explain the behavior of users (Hope, 2004). Apart from motivations to innovate, users may have motivations to collaborate and freely reveal their innovations. These motivations are the subject of sections 2.2.3 and 2.2.4, respectively.

2.2.2 Peer production

Benkler (2006, p. 63) acknowledges open source software as the quintessential example of what he calls peer production. Furthermore, he notes that it is not the only instance of it. Through various examples he demonstrates the viability of the development approach throughout the information production and exchange chains.

Benkler argues that peer production, under the appropriate conditions, has systemic advantages over other modes of production, such as autonomous individual behavior. Due to self-selection of participants, the peer production model is better capable of assigning human capital to information and cultural production processes because it loses less information on who might be best suited to perform a certain task. (Benkler, 2006, p. 373–381)

Particularly important in the context of this research, Benkler (2006, p. 121) states that "Technology does not determine the level of sharing. It does, however, set threshold constraints on the effective domain of sharing.". He further points out that "When use of larger-scale physical capital goods is a threshold requirement of effective action, we should not expect to see widespread reliance on decentralized sharing as a standard modality of production.", Benkler (2006, p. 119). As we will see below, the motivations for participating in communities are generic enough to fit many kinds of objects of production. Benkler argues that the motivations are not new, but that it results from a change in technological barriers.

Benkler provides a sound rationale on why and when a particular mode of production is feasible, be it market-based or non-market peer production. Moreover, he emphasizes the need to understand modes of production other than those that are market or hierarchy based, and to identify and counter policy bias that is suboptimal in terms of provisioning of goods in society (see also von Hippel and Jong, 2010).

To that extent, Benkler's contributions are very valuable to this discussion. It hardly touches upon a combination of market and non-market activity that is visible in the presently studied community. Moreover, the majority of the literature that refers to peer production predominantly deals with information based products. This can partly be attributed by the limited amount of examples available to date, and perhaps to some degree to assumptions about the limited viability of open source hardware. As I will point out throughout this thesis, physical products can increasingly be treated as information products.

2.2.3 Motivations to participate

In the literature, several factors can drive an individual to innovate and to participate in communities such as open source projects. Apart from rational and extrinsic motivations, other incentives are thought to be important determinants of behavior (Ryan and Deci, 2000). Unlike producer-centered innovation, which is primarily profit-driven, user innovation communities operate based on a wide range of motivations (von Hippel et al., 2010, p. 31). This section focusses on four factors that affect the level of this intrinsic motivation: the desire for autonomy, competence, relatedness and meaning. These factors are revisited in section 3.2 of the case study.

Autonomy

In Self-Determination Theory (SDT), (Ryan and Deci, 2000, p. 71) cite autonomy as one of three basic human needs, along with competence and relatedness.

Open source projects are frequently compared to proprietary systems developed by for-profit organizations. However, it is important to consider the nature of the work, in addition to differences in output. The work done in open source communities usually isn't considered to be "work" by the participants, since many of them participate voluntarily. For this reason, it is common in open source communities that members have no formal authority over each other in the community. Dahlander and O'Mahony (2008) argue that progression can be achieved in project-based organizations that reward people with greater authority over collective work even though they do not gain authority over other individuals (see also, e.g., Gacek et al., 2002, p. 9). In other words, the members are autonomous in that they can decide for themselves what they want to work on. Falk et al. (2005) discuss the hidden costs of control, and conclude that close supervision of workers can undermine intrinsic motivation.

In many open source communities, members are not paid or formally rewarded for their participation in the project. Instead, enjoyment can result from the pleasure from learning something new and gaining competence, or a sense of fulfillment results from being able to utilize their talent to solve challenging problems (von Hippel and von Krogh, 2003). Such rewarding properties are intrinsic motivators.

Research suggests that these are beneficial for sustaining creativity and innovation. Amabile (1998, p. 79) states that extrinsic motivation is to be seen mostly as a potential source of creativity problems. Conditional payments, but also career incentives and monitoring are examples of extrinsic stimuli. In the same paper she suggests that intrinsic motivation is a key determinant for creativity.

Because of the relative importance of activities that are enjoyed and the absence of external stimuli, many members can be considered to be intrinsically motivated. This is consistent with recent findings of user innovation in the household sector, where 51% of the innovators' expenditures were reported to be motivated by the enjoyment and learning-related incentives (von Hippel et al., 2010, p. 31). When a person is intrinsically motivated, he or she enjoys the process over specific results. Amabile calls this the Intrinsic Motivation Principle of Creativity: people will be most creative when they feel motivated primarily by the interest, satisfaction, and challenge of the work itself, and not by external pressures (Amabile, 1998, p. 79). Because of this, creative, explorative behavior can be expected to be more salient.

A meta-analysis of several psychological studies by Deci et al. (2001) shows that extrinsic rewards can crowd out intrinsic motivations. It is unclear how the introduction of profit motives into the present ecosystem would create problems (Dahlander, 2005).

The positive and rewarding properties that an individual attributes to the voluntary participation in such a project are beneficial to that project because it is responsible for attracting new participants. In addition, the attracted participants are highly motivated and autonomously decide what they want to work on. Apart from improvements related to the machine itself, a lot of additional physical hardware innovations are being created, as we will see in the case study. For some people, being able to work on other, non-RepRap related innovations may be an important reason to build such a machine.

(Benkler, 2006) "As collaboration among far-flung individuals becomes more common, the idea of doing things that require cooperation with others becomes much more attainable, and the range of projects individuals can choose as their own therefore qualitatively increases. The very fluidity and low commitment required of any given cooperative relationship increases the range and diversity of cooperative relations people can enter, and therefore of collaborative projects they can conceive of as open to them."

Autonomy, according to Benkler (Ibid., p. 21), is at the heart of a shift towards dominance of individual and cooperative private action away from market-based and proprietary action.

Striving for competence

Studies have shown that it is common in open source software projects that enjoyment-based intrinsic motivation is the strongest and most pervasive driver (Lakhani and Wolf, 2003). Also, intellectual stimulation and gaining competence are provided as top motivators for participation. The observation that open source projects often attract new participants based on their intellectually challenging aspects is explained by psychologists as a natural inclination. Ryan and Deci (2000) state that *"the construct of intrinsic motivation describes this natural inclination toward assimilation, mastery, spontaneous interest, and exploration that is so essential to cognitive and social development and that represents a principal source of enjoyment and vitality throughout life"*.

Lakhani and Wolf (2003) also note that in their sample of open source projects, a participants' high rating of the creativity of their involvement was the strongest determinant of the number of hours that were weekly spent in the project. The multi-project sample revealed that the sense of creativity is endogenous to the people within the projects, and not just a property of the project.

Relatedness

Kollock (1999, pp. 228-289) suggested that their attachment or commitment to a particular open source project or group may motivate contributors' actions (see also, e.g., Lakhani, 2003; Muffatto, 2006, p. 61). It is closely related to altruistic behavior that some observers put forward as an important motivational drive (Hars and Ou, 2001). In open source projects, some who strongly identify with the community may actively seek opportunities to help others (Ibid., p. 2). The commitment can be primarily towards the individuals in the group, or, the project as a whole may be considered meaningful, as will be further discussed in the next paragraph.

Meaning

Kollock further points out that by contributing to online projects, participants get a sense of efficacy. People can be motivated by the notion that contributions have an effect on the environment.

Ariely et al. (2008) have found important differences in the levels of motivation between work that was perceived as meaningful and work that seemed meaningless.

2.2.4 Motivations to collaborate

In collaborative dynamics, one can distinguish future oriented and reactive behaviors. Forward-looking Social Approval Reward Hypothesis predicts that individuals will cooperate more when they have the potential to receive feedback on their own contributions. An example of reactive behavior is that when individuals can observe the degree to which other participants are cooperating, it can stimulate a normative response to reciprocate by cooperating as well. (Cheshire, 2007)

This study documents frequent exchange of informational goods, such as ideas, design files and source code, in a community. The altruistic behavior that is commonly seen in communities differentiates itself from patterns found in direct exchanges, in that the reciprocity is directed towards a group and not the individual. When person A gives to person B in the community, he/she does so without an expectation of future interactions with person B. Person A does, however, get benefits from other individuals in the community. Recent empirical findings indicate that indirect reciprocity may be central to what makes generalized exchange work (Mashima and Takahashi, 2008).

Moreover, the availability of selective incentives are brought forward as explanations as to why people are motivated to contribute to a public good, such as in online communities. Replicability and non-rivalrous properties of the digital goods are important for these selective incentives to have a more profound impact on motivation (Cheshire, 2007). Replicability of digital goods, as pointed out before, is facilitated by our improved communications infrastructure. Similarly, the fact that the information is digital, the supply is not scarce since transferring digital goods to others does not deplete the original stock.

Chapter 3

Case study

One of the more ambitious open design projects is the RepRap project. Its goal is to collaboratively develop a low-cost fabrication device that can, to a large extent, produce a physical copy of itself. The RepRap machine is often described as a 3D printer, one that creates strong, tangible objects of arbitrary shape. RepRap is short for Replicating Rapid prototyper. Based on digital design files, these machines can be used to fabricate a diverse range of physical objects of value to the user. RepRap users frequently exchange design files of physical objects, for free and under open source licenses. One of these collaboratively developed designs is the RepRap machine itself. Users of RepRaps have the tools to fabricate modifications for the machine that they operate. A large share of its parts is designed to be printable on the machine itself.

Rapid prototyping machines have existed for over 20 years, but never at a price point attractive for domestic and hobbyist use. In contrast to subtractive processes, that start with a workpiece and remove material to yield the desired object, rapid prototyping is an additive process of forming objects. The so-called Additive Manufacturing (AM) industry is introducing lower-costs AM machines, but so far most of them are above 10,000 euros. The RepRap is designed to be built for less than 500 euros, which has allowed a wider set of people to experiment with the technology and improve it.

This chapter looks into this user innovation process by seeing who is innovating, how they are organized, how they are motivated and the role of the tools and infrastructure that they adopt and develop.

We begin this chapter with a look at how the project was initiated. We will then identify properties that enable the form of collaboration that is observed in the RepRap project, resulting from its replication aspect and the fact it materializes digital input. One cannot fully understand an instance of innovation or a collaborative process unless one knows *who* is doing it. In chapter 4 the findings from the survey, will shed further light on the participants' previous experience, motivations and functional relationship to the invention and innovation assets.

3.1 RepRap as a platform and a community

In 2004, Adrian Bowyer, a professor at the University of Bath, proposed the idea of creating a rapid prototyping machine that could make a significant fraction of its own parts. His goal was to make this technology accessible to anyone who wanted it[1]. Bowyer mentions that the three important qualities of his envisioned machine were (1) that the number of them and the wealth they create could grow exponentially[2], (2) the machine becomes subject to evolution by artificial selection and (3) that it creates wealth with minimal dependence on industrial manufacturing[3].

3.1.1 Unique characteristics and adoption

For diffusion of the invention to occur, potential adopters need both sufficient incentives and the means to obtain it. Most of the practical reasons for adopting the machine result from its wide range of applications, low switching costs between different production jobs and the benefits of using digital designs as input. Within the build volume of the machine, there are few restrictions on the shape of the object that it fabricates. This is relatively unique and is a result of the layer-based technology used. Moreover, the specific object that it fabricates depends on the digital design file that is selected. Very significant is the ease with which designs can be distributed, since a large fraction of the design and fabrication information is codified into digital files or online records. A resulting attractive feature is that physical upgrades and variations can be fabricated with the same machine, and that these variations can be shared digitally with relative ease. This enables the artificial selection (ad 2), carried out by relatively independent individuals and organizations (ad 3). Note that the third quality closely matches von Hippel's third condition under which horizontal innovation networks can emerge (as discussed in section 2.2.1).

3.1.2 Evolution and governance

After Dr. Bowyer's initial proposal to build a RepRap in 2004, experiments at Bath University were conducted of which the results were shared online. This captured the interest of a widely distributed audience that joined the experimentation and pooled their knowledge. In the first year, less than 10 people were involved. Most notably, Vik Oliver, an open source enthusiast from New Zealand, developed and built several of the early prototype machines[4]. Zach Smith, a web-developer based in New York City, designed circuit boards and started selling kits through a foundation he set up in conjunction with the core team.

[1] From a personal interview in February 2010.

[2] As we will find in chapter 4, the number of RepRap's installed is indeed growing exponentially.

[3] From http://www.bath.ac.uk/~ensab/rapid-prototyping/ retrieved 3 January 2005, via The Web Archive

[4] Oliver, V. Construction of Rapid Prototyping Testbeds Using Meccano. May 2005

Within the RepRap community, with regard to the level of involvement, you can distinguish between the core and peripheral community. When more people volunteered, an official core team was assembled including most of the people who were involved early on. Over time, more people from the peripheral community were included in the core team. They are voted on board by unanimous vote. The core team can be considered a non-hierarchical group. New core members are invited based upon merit. If you engage more heavily in problem solving within the community, you're more likely to progress to its center. Moreover, the core members take some level of responsibility of coordinating work, yet for many issues the whole community is consulted. Historically, the core team has taken decisions regarding the architecture of designs and infrastructure for collaboration. In the absence of formal authority, everyone in the community is free to disagree with decisions and implement things in a different way. This way they can prove the value of a different approach. Most individual innovators are in control of their own budgets and decide for themselves what to spend their time and money on[5]. The participants autonomy is discussed in detail in section 3.2.1.

3.1.3 Technological innovations

Adopters of RepRap technology have a valuable set of prototyping tools at their disposal that also allows them to improve the technology itself. Moreover, those benefiting from its use will have an incentive to improve it. Improvements include added functionality, improved existing functionality and performance, increased ease-of-assembly and use, lower-cost, more suitable (e.g., easier-to-acquire) components, specialization towards a certain application, extended auxiliary tools, interoperability with other systems, improved design architecture and developing or refining operating techniques. In addition, several layers of the stack of technologies used can be discerned. These include, physical/mechanical, electromechanical, microcontroller firmware, etc. See appendix C for a list of innovations in each of these categories.

A sustainable innovation process relies on radical and incremental innovations. In other words, the viability of communal development of designs of physical objects relies on the ability to generate both types of innovation.

3.2 Motivations to participate

In interviews with several members of the RepRap community the motivations identified in section 2.2.3 seemed to be present among people choosing to participate in the project. Autonomy, the desire for competence, relatedness and meaning appear to be important motivators.

[5]One exception to this is the budget that is available from ad revenues from the RepRap websites. The core team offers to pay some of the costs that an experimenter in the community may incur. The ad revenue has been used for printing parts on commercial machines early on in the project, for air tickets and currently it is being spent on consumables for printing sets of RepRap parts at cost.

3.2.1 Autonomy

As mentioned in section 3.1.2 about governance, and like in any open source community, there is no formal authority over members in the community. The members are autonomous in that they can themselves decide what they want to spend their time and money on. Consequently, they will generally not work on aspects that they do not enjoy working on.

Everyone who works in the RepRap project mostly manages his or her own budgets, because it's usually their own money they are spending, in contrast to organizational spending. For example, use of a company resource such as money may require approval. Spending it unwisely in the eyes of your colleagues or superiors might be a source of tension or even conflict. Such a potentially adverse effect is discussed in the theoretical part (section 2.2.3). By contrast, in the RepRap community there is no need to convince people of the value of a costly experiment for the sake of approval. This means that even if an approach may not seem like a viable alternative to most people in the community, it can and will still be tried as long as at least one person is motivated to do so.

The sought autonomy, however, should not be mistaken for independence. The people that work on the RepRap project have a good sense of the value that others have brought to the table and that they could never have done all of the work by themselves. Also, most people acknowledge that the social component present in the community is important to them.

The positive and rewarding properties that an individual attributes to the participation in the project are beneficial to the project because it is responsible for attracting new participants. In addition, those participants who are attracted are not only highly motivated, but also creative and can autonomously decide to experiment and innovate as much as they like.

With the completion of their RepRap 3D printer a person acquires both a powerful tool and the skills to create new physical objects. The people in the RepRap community tend to be inclined toward working creatively on challenging problems. Apart from improvements related to the machine itself, a lot of additional innovations are created. For some people, being able to autonomously do work on other, non-RepRap related innovations may be an important reason for building such a machine.

3.2.2 Striving for competence

Below is a small, random selection of reasons given by people who have built their own 3D printer:

"Fun, learn new skills."
"To learn about programming and using Arduino"
"1) For the challenge of building it 2) To improve upon the design, or test fundamen-

tally new designs that could be easier to reproduce"
"I am currently studying Engineering and saw building a 3D printer as a valuable way to gain skills to help me inter the industry."
"Intellectual, manual and creative stimulation. All of which are sorely lacking in day job."
"Interest and sense of achievement"
"It's good fun as well as a learning experience."
"because i like learning and understanding stuff"
"The challenge"
"personal development, fun intellectual thing to keep me occupied [...]"
"To help further my skills as a designer and modelmaker [sic.] for work"
"i wanted a good personal challenge"
"I am also using it as a basis for learning more about electronics and robotics."
"Technically challenging, fun potentially useful, developing skills."
"Learning robotic skills"

3.2.3 Relatedness

Social behaviors, such as following other users' blogs and interaction via social networking websites, seem to be present. The online communications channels used, include the RepRap forums, the blogosphere, wiki's, Twitter and IRC. While an important part of these media are used for dissemination of information, the fact that people collaborate in a project and share similar motivations and goals, suggests that social aspects are at least of some importance. In addition, physical gatherings are becoming popular because it is increasingly likely to find several RepRap users nearby. This also tells us to expect these behaviors to change over time.

The survey included several questions on motivations to help others, the role of community assistance in problem solving and the role of local groups. Because it is mostly quantitative data resulting from the survey, it will not be addressed in detail here, but instead in section 4.1.5.

3.2.4 Meaning

The work done by members of the RepRap community is generally perceived to be meaningful. Moreover, building a RepRap and improving it is a process of gaining competence.

The meaning that the project has for these people makes them highly motivated. In the survey, out of 50 randomly selected responses, 9 respondents specifically took the time to further elaborate on why they are motivated to participate in the project. The quotes serve to give an impression of how meaningful the project can be to those involved in the project:

"Participating in the future"
"not that difference from the personal computer revolution"
"participate in one of the most exciting open source projects that exist and be part of something that will have a huge impact on manufacturing goods, the world, economy etc."
"because a new revolution is upcoming!"
"I love the potential of the Reprap, and want to help develop it to the point where home 3d printers become widespread."
"Hope to change the world by democratizing design and manufacture of material goods. good for freedom, good for planet."
"I want to be part of something like the reprap that I think will be extremely important (like having an apple II in the late 70's)"
"Every home needs a replicator"
"The thought of helping to make 3D printing far more accessable [sic.] to most households and third world countries in the hopefully not-too-distant future."

3.3 Adoption and development of sharing infrastructure

The Bath University groups' choice for the open source license and for publicly documenting it on the web helped others reproduce their inventions. Initially, physical prototypes 3D printed at Bath University in the United Kingdom were physically shipped to Vik Olliver, an active member based in New Zealand. At a later stage an upload and download would suffice and the object would be fabricated in the recipient's home.

The large physical distance and timezone offset of community members makes asynchronous communications the most practical option. The benefit of most asynchronous ways of communicating is that it is easily recorded and redistributed[6]. People can access the needed information and post feedback from anywhere at any time. At first, general purpose infrastructural tools such as mailing lists, blogs, forums, wikis, public video sharing platforms (Youtube) and code repositories were deployed or adopted[7].

In November 2008, a dedicated design sharing infrastructure, called Thingiverse[8], was developed by Zach Smith. Zach was an early RepRap community member who was, at the time, a web-developer employed by Vimeo, a social video sharing service. Thingiverse included 'social software'[9] features from the start, such as the ability to provide feedback to the content that was posted, the ability to rate it and to create 'folksonomies'[10]. Section 4.1.4 provides some statistics of the usage of Thingiverse.

[6]For synchronous systems, all parties involved in the communications need to interact at the same time. Asynchronous messages, by contrast, are usually stored and retrieved.

[7]For a description of version control systems and code repositories, see von Krogh et al. (2003, 1220))

[8]Thingiverse currently hosts over 4000 designs for objects that you can fabricate with digital fabrication tools. See `http://www.thingiverse.com`.

[9]Social software is a term coined by Clay Shirky, it concerns software for which a group is considered as the primary user, not the individual.

[10]A folksonomy is a system derived from the practice of collaboratively managing tags to annotate and

The fabrication capability of the 3D printers can also be considered an important infrastructural tool. It allows open hardware developers to design, fabricate and share new innovations, to adopt others' innovations and to test out modifications and alternative versions of existing designs. In the following paragraphs we will go over the evolution of the RepRap machines, including the emergence of an ecosystem of vendors and user innovators.

There are three official versions of the RepRap. Each of the official RepRap's can produce the custom bits needed to build another machine of the same version, or of the next one. It is ensured that there is an upgrade path towards the latest version, without relying on outside sources. For the parts that it cannot produce, the community has found many affordable alternative that do the job and that can acquired easily. With each new model released, contributions from the rapidly growing peripheral community became progressively more substantial.

Not only did the RepRap design evolve through community contributions, several RepRap users have made derivative versions that they could then start selling (more businesses and the derivative models they sell are listed in appendix A.). As mentioned in section 2.2.3, extrinsic motivation may crowd out intrinsic motivation. However, for the opportunity costs of selling machines and parts, no crowding out was observed. In most cases these user-founded businesses were accepted by the community because they made it easier and more affordable to obtain the needed parts. Most of these businesses provided the machines in kit-form, for the user to assemble. Several of these businesses are reported to have sold thousands of complete kits, selling them at a higher rate than Stratasys Inc., who have for 7 years been the unit sales leader in the industry[11]. The community-centric businesses also greatly benefit from the community, since it provide a stream of updates and modifications to the machines that they sell. In the case of Makerbot, these modification are contributed at a rate beyond what would be feasible for in-house development by any single firm in the industry[12]. Many user innovations are integrated into the main designs or become products. Moreover, apart from machine upgrades, users and businesses alike benefit from an increasing amount of 3D-printable content that is available for free, making it increasingly valuable to have a 3D printer and easier to get one.

Along with the growing demand for RepRap machines there is a growing need for the 3D printed parts that they are made from. As the project advances, more people are capable of printing out those parts for which there is a large demand. Some individual RepRap members report having printed more than a dozen sets of parts for others. Re-

categorize content. It is a portmanteau of the words folk and taxonomy.

[11] For instance, Wohlers' reports say that BitsFromBytes now has 17 percent of the global market for additive manufacturing. From: http://www.designnews.com/article/509073-Open_Source_Systems_Emerge_in_3D_Printing.php Similarly, Makerbot had sold over 2000 units in the 18 months since they were founded in April 2009. From: http://blog.makerbot.com/2010/09/23/gidget-the-2000th-makerbot-to-appear-at-maker-faire/. The systems that originated from the RepRap project have come to dominate the market in terms numbers. One of the larger vendors, 3D Systems, have recently acquired BitsFromBytes (see appendix A).

[12] At the time of writing there were 118 objects on Thingiverse tagged as upgrades to the Makerbot's Cupcake CNC model, the majority of which is community provided.

cent advances in optimizing the 3D printing process, such as continuous printing, allow a further lowering of the manual labor component for 3D printed parts for RepRap machines and other innovations. Printing directly onto a conveyor belt was pioneered by Charles Pax, a user innovator who was later employed by Makerbot. The Automated Build Platform was published under an open source license on September 13 and it received community improvements on September 14th of 2010[13]. The price for parts on eBay is currently in the order of 150 to 300 dollars. These parts come almost exclusively from the RepRap community as most rapid prototyping service bureau's would charge more than tenfold this amount. It is expected that new cohorts of RepRap owners can supply increasingly large markets with greater volumes of parts. Moreover, a distributed supply network, even one that is moderately dense, allows much more efficient distribution in terms of logistics since the parts can come from suppliers increasingly close to the buyers. Furthermore, the materials that the machine can process is expanded through user experimentation. RepRap's have also been used for isolation routing of printed circuit boards (PCBs), allowing an important part of the electronics stack to be fabricated using the digital files to control the RepRap machine. Many of the electronics subsystems are also developed under open source licenses.

3.4 Case analysis

Industrial product development and engineering are generally regarded as activities requiring payments and career incentives to induce effort. Similarly, before open source software was studied more extensively, the notion that people would develop software and release it for free was puzzling to many observers. The primary motivations within the RepRap community are consistent with the most important motivations identified in studies of open source software communities. The community appears to consist of highly motivated, creative and innovative individuals who are often looking for a challenge, an opportunity to learn, share and make a difference. Considerable effort is invested in the project while the results are made available to anyone. The sharing infrastructure both makes sharing more practical and more attractive, since it allows a developer to get feedback. In the literature, there are indications that this may be an important motivator (section 2.2.4).

The case study explores the operation of the open source development process in the RepRap and directly related communities. Many of the community members possess a fabrication capability that the average person does not have access to. While this does limit the present day generality of the case study findings, there are many reasons to expect a high likelihood of personal access to digital fabrication in the near future. Among them are the fact that traditional vendors are selling their machines at increasingly low price-points, prototyping service bureaus like Shapeways and Ponoko are for the first time targeting creative consumers instead of industrial markets and the

[13] See: http://www.thingiverse.com/thing:4107

rapid growth of RepRap and RepRap related ecosystems of user innovators and businesses (see section 4.1.1 of the quantitative analysis). The fact that the technology is able to produce objects of increasingly high quality and that freely accessible design libraries are expanding rapidly, indicates that widespread adoption is not only plausible but almost inevitable because of the lowered threshold and increasing value of personal fabrication. As new cohorts adopt the technology they will increasingly demand further maturation of these technologies. Taken together, mass adoption and the anti-rival logic, as suggested by Weber (2004), allow collaborative development to have significant implications for the provisioning of goods in society.

The diversity of community members and other actors in the ecosystem, with respect to motivations and innovation assets held, reflects the many technological aspects being given attention (as seen in section 3.1.3). Another explanation is that user innovators are found to create innovations with more functional novelty while manufacturers tend to be better at productizing and refining – innovating along already existing dimensions[14]. The emergence of market-driven entities into the community's ecosystem appears to extend the range of motivations, rather than crowding out motivations or relegate user innovators to become supplier-dependent consumers. Benkler (2006) mentions that *"this form of link between a commercial firm and a peer production community is by no means necessary for a peer-production process to succeed; it does, however, provide one constructive interface between market- and nonmarket-motivated behavior, through which actions on the two types of motivation can reinforce, rather than undermine, each other."*

In section 3.3 special attention is given to the role of such accessible and affordable digital fabrication capabilities and their effect on collaboration. These capabilities affect the cost of development, production, reproduction and distribution of physically embodied innovations. By making embodied knowledge more communicable, it affects the locus of innovation, as we will conclude from the analysis in section 5.3.2. Technological advances thereby increase the fraction of a project's modules that can be developed through the open source development process, reducing the dependence on external parties.

In section 3.3 I mentioned that with every new version of the machine, more distributed development patterns become visible. The may be partly due to a project's natural progression, as was observed in an empirical study of several open source software communities by Crowston and Howison (2005). However, I argue that, before adopting personal fabrication technologies, a developer's ability to contribute to parts of the RepRap's physical design is significantly restricted. Moreover, the incentive to improve a part may not be as strong. As more people in the RepRap community obtained the ability and incentives to improve parts that they use, this has enabled

[14] See von Hippel and Riggs (1994) for an analysis showing how novel functionality emerges from users. von Hippel (1976) also found this distinction between major and minor inventions that were predominantly users and manufacturer-centric, respectively. The complementary nature of user an manufacturing innovation is discussed by Henkel and von Hippel (2004).

the distinct distributed development methodology that characterizes many successful open source software communities.

Chapter 4

Survey

Empirical data was gathered by administering a survey to those who build and/or operate open source 3D printers. The final survey was administered via the web. It was available at "http://www.reprapsurvey.org" from 25 February to 18 March 2010. Please see appendix D for a copy of the survey. It is expected to have a response rate of 20% to 25% (see Appendix B). The survey is quite extensive (up to 72 questions when applicable) and on average took 13 minutes and 28 seconds to complete. 386 complete responses were received.

The survey was divided into the following sections:
A. Type of user
B. Adopting the machine
C. Innovating the software
D. Innovating the hardware
E. Thingiverse
F. Demography and general questions

The survey tracks the entire process from adoption of the platform, to development of innovations and, where applicable, their free revealing and their diffusion.

Section A and B contain questions regarding the adoption of existing technologies. Problem incidence and problem-solving is measured. Specific attention is paid to whether or not the user has a local support group. In section C and D we track newly created innovations and whether and how they are revealed and diffuse to others. Thingiverse.com is a website for sharing digital designs of physical objects. The majority of the users of this website is affiliated with the RepRap project and many of them have their own fabrication devices. In section E on Thingiverse, we focus on the community based prototyping of new objects and the fully distributed manufacturing.

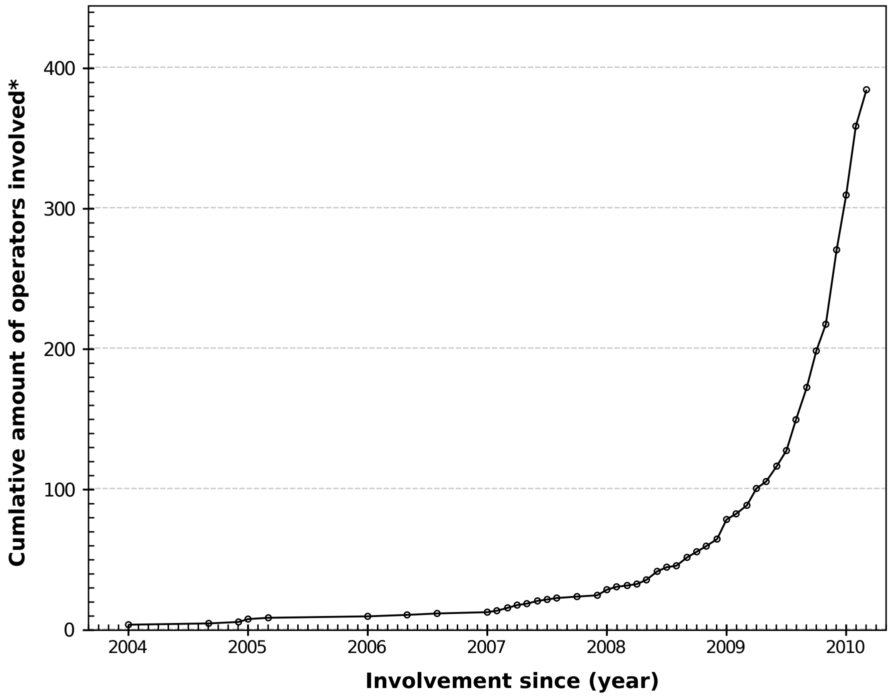
4.1 Overview of the results

4.1.1 Community growth

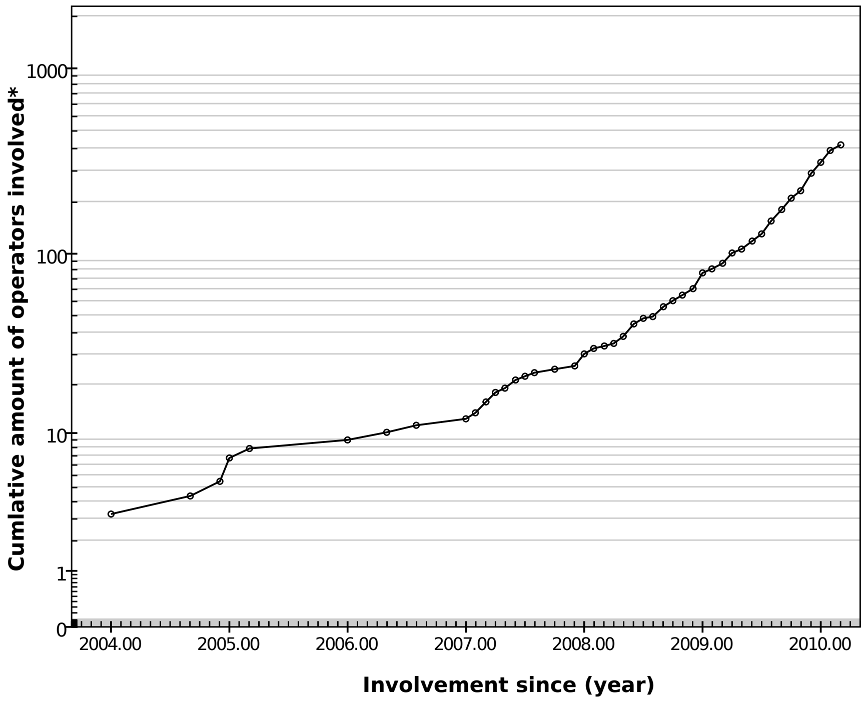
One of the first remarkable findings derived from the survey is the growth characteristics of the community. As shown in figure 4.1 and table 4.1, most people who become involved in the project and adopt the technology have done so fairly recently. The adoption rate increases so fast that new adopters outnumber all those who joined more than 6 months ago. It also holds another powerful message. An attempt to measure the size of the community is prone to be outdated when analysis of the collected data is complete. Yet, particularly over the long run, the precise size is far less important than its growth rate. These figure show that the community is able to attract increasingly large quantities of participants. The growth rate already factors in a certain amount of people who have become inactive, since they are unlikely to have seen the invitations to participate in the survey during the period in which it was available.

Regression-fitting this growth curve yields a duplication of the community every 6 months and a 10 fold growth every 20 months[1]. If this growth rate would continue unabated this means that there would be 26 million operators by 2016. Obviously, extrapolating this far out of the data assumes that there are no fundamental changes to growth characteristics. Because of the rapid exponential growth, a logarithmic graph is provided in figure 4.1(b).

[1] Using a non-linear least squares fit (Levenberg-Marquardt nonlinear regression).



(a) **The cumulative amount of sampled operators involved.**



(b) **Depicted on a 10-log scale.**

Figure 4.1: The cumulative amount of sampled operators involved. ∗ Note that the actual number of operators is higher, depending upon the ratio between population and sample size. This ratio is estimated to be, roughly, between 4:1 and 5:1.

Table 4.1: The joining behavior of sampled RepRap operators

	Number joined	*Total joined so far*	*Annual growth rate*[a]	*Doubling time*[b] *(months)*
1999 Q4	1	1		
2004 Q1	4	5	146.04%	22.0
2005 Q1	3	8	160.00%	17.7
2006 Q1	1	9	112.50%	70.6
2006 Q2	1	10	152.42%	19.7
2006 Q3	1	11	146.41%	21.8
2007 Q1	4	15	185.95%	13.4
2007 Q2	5	20	316.05%	7.2
2007 Q3	2	22	146.41%	21.8
2007 Q4	2	24	141.63%	23.9
2008 Q1	7	31	278.36%	8.1
2008 Q2	10	41	305.98%	7.4
2008 Q3	10	51	239.41%	9.5
2008 Q4	13	64	247.99%	9.2
2009 Q1	24	88	357.45%	6.5
2009 Q2	28	116	301.93%	7.5
2009 Q3	56	172	483.37%	5.3
2009 Q4	98	270	607.21%	4.6
2010 Q1[c]	114	384	409.14%	5.9

[a] The annual growth rate was calculated as $G_i = (C_i - C_{i-1})^{\frac{1}{t_i - t_{i-1}}}$, where C_i is the total amount from the sample that have joined listed in row i and t_i is the date for this row.
[b] The doubling time in row i is $\frac{\log(2)}{\log(G_i)}$.
[c] The data for this line is incomplete because the sampling period ended before the second quarter of 2010, this means that the actual numbers are higher.

For October 2010 the population is estimated to be between 3,872 and 4,840 participants. This is based on the calculation listed in equations (B.3) and (B.4) of appendix B.

Not only do RepRaps spread to more individuals, the individual operators of working machines have the capability to make more of them. Respondents were invited to list the machines they had. 52% have at least one working machine. The average operator has 1.52 machines (working or being constructed). More than half of the respondents had multiple distinct types of machines (table 4.2). They possibly have several instances of each distinct type of machine they own.

It's common not to make copies of the same machine, but rather later versions or variations. While there are some substitution effects, some commonly taken upgrade paths can be identified. So-called "bootstrap machines" can be constructed from ubiquitous parts available in hardware stores, or purchased as kits, which are available from various suppliers. Bootstrap machines, in general, do not depend on 3D printed parts but can be used to make the parts for a RepRap, which *is* capable of reproducing its own parts. The fact that the 3D printing capability was used to make the first RepRap

Table 4.2: Distinct number of machines per operator

No. of distinct types of machines	*Frequency*
1	237
2	108
3	28
4	9
5	2

designs shows that this capability supports the creation of subsequent physical innovations. It also shows that, for the growing population of 3D printer operators, these machines provide an upgrade path to even higher-quality 3D printing capabilities, based on freely revealed, user-developed designs.

Because most RepRap models are not finished products bought whole, but rather made from parts that one acquires from one or more sources, many people are in various stages of building a machine. The large proportion that is building a machine is explained by the high ratio of recent adopters, as seen in figure 4.1.

4.1.2 The level of activity

This section focusses on the time and money spent on activities that have to do with the 3D printers. The average community member spends 10.41 hours working with or developing their machine (n=376). In table 4.3 several activities are listed that community participants spend their time on.

Table 4.3: Time the average individual spends on using and developing the machine

Time spent (weekly)...	*hours*[a]	*percentage*
...building the machine; getting it to work	4.9	47.12%
...printing objects	1.7	16.56%
...developing improvements[b]...	1.5	14.53%
...in order to print what I need, or	0.7	6.47%
...just to make it better.	0.8	8.06%
...helping other users	0.9	8.56%
...improving skills	1.4	13.23%

[a] The absolute average number of hours spent per activity were derived from the relative expenditures in time that were reported in the survey, multiplied by the average number of hours, 10.41 hours.
[b] This activity is the summation of the two activities listed below it and is used as an indication of average innovative input.

The actual numbers may be lower because there may be a tendency to overrate the time spent and because the people that took the time to complete the survey may be the more active participants. Still, when multiplied by the size of the community, the effort that goes into the development of improvements is quite substantial. Also, there is a considerable amount of effort put in to acquire a platform that will enable its users to innovate in open design. The level of R&D (*b* in table 4.3), in aggregate, is between 145 and 182 full-time equivalents (based on 40 hours work weekly). By comparison, Stratasys, the unit sales leader in the additive manufacturing market had 361 full-time employees and 42 contractors in total. This includes departments ranging from manufacturing, marketing, engineering, customer support and sales[2].

Even if the aggregate R&D input in the community is lower than that in the largest vendors in the industry, the community experiences more than 400% growth annually while many organizations in the industry have had workforce reductions in recent years. Also, note that there are important differences between thousands of people spending a few hours of their free time and smaller group that spends many hours per month as part of their jobs. While the former may be less efficient, it allows for effects such those characterized by Raymond as Linus' law.

The total amount of money that the respondents spent so far, was 401,149 dollars, averaging an expenditure of 1,045 dollars[3]. The estimated expenditure for the whole community is expected to be between 1.6 and 2.0 million dollars until March 2010. If patterns of expenditures remain representative for the current population, this would equal between 4.0 and 5.0 million in October 2010, however this is less accurate as the costs of getting a good machine may have been lowered and its value increased, the effects of which are hard to predict. Expenditures that respondents indicated for developing their innovations were 7,174 and 31,135 dollars for software and hardware respectively. These user-innovation expenditures account for 9.5% of the total expenditures, totaling between 153,000 and 190,000 dollars for March and roughly 382,000 to 478,000 dollars for October 2010[4]. Users who do not innovate may have been less inclined to participate in the survey, so population estimates may be inflated to some degree.

4.1.3 Innovation in software versus hardware

Interestingly, within the sample, 26.3% indicated they had modified the software and 49.2% indicated they had modified the hardware of the RepRap technology. In the discussion in section 4.2, some explanations are provided for the high proportion of hardware modifications.

If there is no diffusion, a modification is just a local invention and will have a limited impact. A modified software or hardware setup is not necessarily completely revealed

[2]From: SEC 2010 Annual Report filings. Form 10-K, Stratasys Inc., 2010. The workforce figure is also for March 2010.

[3]Use of several currencies was allowed. Where applicable, currency conversion was done with the exchange rate of March 2010.

[4]Stratasys Inc., stated that for the years ended December 31, 2009, 2008 and 2007, their research, development and engineering expenses were approximately \$7.7 million, \$9.0 million and \$7.5 million, respectively. From: SEC Annual Report filings. Form 10-K, Stratasys Inc., 2010.

to everyone in the format best suitable for modification by others. It may have limited diffusion, such as within (geographically concentrated) subgroups. The innovation may be shared incompletely, e.g. a photo is shared but not the design files or design files are shared but not documented. This in turn limits the level of collaboration that is possible. However, it is not uncommon for an innovation to be detailed extensively in blog posts and/or wiki pages. One would expect a higher geographic concentration when it concerns a hardware modification. While this may be the case, it did not limit the level of collaboration severely, as there is more collaboration in the hardware than software even when adjusting for the high hardware-to-software ratio (*a* in table 4.4). This can only partly be explained by slightly higher levels of free revealing in hardware – 121, or 64% – compared to software – 62, or 61%.

An individual's motivation and perception of difficulty can determine which innovations will be developed. This depends, to a large extent, on the personality of the individual and the structure of the incentives. If the incentives have to do mostly with learning, a difficult task might be deliberately undertaken instead of an easy one. On the other hand, difficult tasks, or tasks where skills may be limited may be avoided by others. Rather than trying to fully understand the complex interactions of these hard to measure properties, we let people judge for themselves to what extent others had adopted their innovations and what difficulties they would encounter. With hardware, there were less adoption difficulties anticipated (*b* in table 4.4).

Table 4.4: Software versus hardware innovation in the RepRap community

	Software			*Hardware*		
	%	*innovations*	*of total*	%	*innovations*	*of total*
Types of innovation						
New functionality	50%	50	101	37%	69	189
Convenience	76%	77	101	65%	123	189
Performance	41%	41	101	53%	100	189
Novelty	33%	33	101	22%	42	189
Level of collaboration[a]	26%	26	101	33%	62	189
Free revealing	61%	62	101	64%	121	189
No exclusion	73%	45	62	81%	98	121
Diffusion of innovations						
Expected diffusion	30%	30	101	22%	42	189
Local diffusion only	0%	0	12	18%	3	17
Ease of adoption[b]	11%	11	101	26%	49	189
Adoption blockers						
Too specific to user need	40%	40	101	16%	30	189
Too experimental	56%	57	101	47%	88	189
Benefits not apparent	3%	3	101	9%	17	189
Long time to implement	5%	5	101	13%	24	189
Sticky information	5%	5	101	4%	7	189
Expensive	1%	1	101	3%	6	189
Difficult to integrate	7%	7	101	6%	11	189

[a] There is more collaboration in hardware than in software.
[b] The developed hardware innovations are perceived as easier to adopt by others.

4.1.4 Utilization of open source hardware development infrastructure

Thingiverse is a sharing platform for designs of physical objects (introduced in section 3.3). It helps with the dissemination of design files, documentation and discussions. It was studied because of the wide acceptance and adoption among the community and relatively few members from outside of the RepRap community. In the survey, 68.6% have reported their use Thingiverse for retrieving and/or publishing designs. Table 4.5 show several parameters that were derived from the survey that shed light on the level of usage of the infrastructure. This includes the design, dissemination and distributed manufacturing of thousands of open design products.

Table 4.5: Utilization of Thingiverse for sharing hardware designs

Parameter	Sample value	Lower population estimate[a]	Higher estimate[a]	n^b
Average retrieved objects printed	13.62	-	-	204
Total retrieved objects printed	2,778	11,112	13,890	204
Average no. of designed objects	30.20	-	-	283
Total no. of designed objects	8,547	34,188	42,735	283
Average no. of designed objects uploaded	1.62	-	-	283
Total no. of designed objects uploaded	460	1840	2300	283

[a] The population estimates are respectively based on a 4:1 and 5:1 population to sample size ratio. These are tentative estimates for March 2010.
[b] *n* is the number of applicable responses from which the value was derived. The averages are for participants who do use Thingiverse.

On October 11th 2010, 1486 of 3466 designs (43%) on Thingiverse had been uploaded in the last 6 months. This suggests that it the submissions have lower, but still substantial growth characteristics similar to the growth of the community.

The majority of these designs have an open source license. This enables people to create derivative versions without having to ask for permission. On Thingiverse, more than 10% of the designs are derivatives[5]. The ability to create a derivative allows people to get more precisely what they want with less effort and allows designs to evolve more quickly and further.

4.1.5 Collaborative behavior

People are motivated to collaborate for various reasons. The survey tells us about what motivates people to adopt the machine and to innovate. Other questions from the survey mostly focus on the resulting collaborative behavior, such as the giving and receiving of assistance. People were motivated to build and use the machine for several reasons. Respondents indicated the prospect of helping others was 8.0% of the reason to adopt the technology. People most frequently indicated that they help others "sometimes" (question A5d). The sampled participants on average reported spending 0.9 hours per week helping others (see table 4.3). The sources that were used by people are listed in table 4.6, along with the percentage of respondents that indicated their use

[5] In fact, 295 of 3,486 designs (8.45%) were formally listed as derivatives, but the actual number is expected to be higher as many people do not indicate this formally, but write it in the description.

Table 4.6: The use of various information sources

Source consulted	%
Online wiki's, forums and blogs (e.g., RepRap site, BfB, Makerbot)	95%
Online video sharing sites (e.g., Youtube)	49%
Personal communication with other users (e-mailing, chatting, telephone calls)	56%
Personal assistance by other users (clubs, one-to-one visits)	41%
Physical inspections of other machines	20%

of this source. The reported use of personal communications and assistance indicates that these forms of collaboration are very common.

Question A8 of the survey was supposed to tell us about the way in which people help each other. However, due to a mistake in the configuration of of this conditional question the resulting data may not be representative, so it is not used. While we are unable to quantify these occurrences, there are examples known of people helping each other in various ways. It is done by posting information on the web, participating in online discussions and even sending others physical tools and parts.

4.1.6 The role of local communities

The relative disadvantages of physically embodied innovations, compared to immaterial innovations, may have an effect on their diffusion and of diffusion of accompanying knowledge. For instance, within a certain local group that meets frequently, a lot of knowledge may be developed around a specific physical object, such as the techniques of building it, how to handle and apply its materials, etc. How important, then, are the benefits of local groups to people in the RepRap community? If they are important, those working without them will be disadvantaged. This, in turn, could restrict collaborative hardware-related projects to those where multiple participants can physically meet. This would limit the range of viable projects to those for which it is likely to find fellow enthusiasts nearby, or to those where a more generic local group suffices. In any case, it would drastically limit the level of distributed activity that often characterizes collaboration in open source software.

78% of the respondents had software and/or hardware problems when building one or more of their machines (n=298). Incidence and resolution of the stated software and/or hardware problems were not correlated with any particular type of information source consulted (either public online discussions, personal communications or physical meetings). People did not face more problem in hardware or software when they were not member of a local group. However, being in a local group of RepRap users did have some impact on problems solved in hardware (Pearson Correlation of 0.135,

$\alpha \leq 0.024$). Table 4.7 shows the percentages of hardware problems that were solved. This correlation was not statistically significant for software.

Table 4.7: Effects of local groups on problem solving

Did you solve the hardware related problem?	In local group[a]	Not in local group[b]
No, or not yet	12.9 %	25.2 %
Yes, partially	42.9 %	41.4 %
Yes, completely	44.3 %	33.3 %

[a] In a local group: n=70
[b] Not in a local group: n=210

This is an indication that both software and hardware related problem-solving activities do not require on the presence of local groups. Still, successful problem-solving in hardware is facilitated by being in a local group of RepRap users.

4.2 Discussion

To some extent, the fact that you can develop hardware in this project might be an attractive feature of the project, leading to hardware developers being overrepresented in the RepRap community. Interestingly, while hardware modifications are more common, the majority of the current participants indicated they had more experience in software than hardware development. Programming software was indicated as the only category where 32.1% indicated that they were experts. In other categories such as experience with mechanical hardware, electronics and CAD software and digital fabrication only 11.1%, 13.2%, 12.9% and 5.5% respectively ranked themselves as experts (n=380). In this community, the large share of people familiar with software development practices may increase people's tendency to also apply these practices to hardware development.

A possible explanation for the large share of modification in hardware is the effort required to replicate the physical setup of a machine. If a builder of a RepRap sees an alternative approaches as viable, this may seem relatively appealing. For instance, if a builder has a limited access to the required parts he or she may opt to use an alternative that is available to him or her. The resulting variety in machine implementations can prove to be both a strength and a weakness of the distributed approach. It favors creation of a whole library of alternative setups that are revealed and documented by the users themselves. This offers people with limited access to certain parts or those interested in properties of the alternative setup with a host of options to choose from. It also encourages a very robust and wide search for solutions, through which one of the alternatives can become a best practice. Moreover, it allows a variety of machine variations at different price points, optimized towards a certain property (e.g., speed or accuracy) or with an entirely new capability (e.g., printing ceramics or metal). The downside of such variety is that it becomes harder to diagnose problems and users can become overwhelmed by too many choices. In software, the fidelity of a replicated copy is not so much an issue, so the creation of a variety is usually a deliberate choice or comes for a users' unawareness of the existence or preference to rewrite a section.

Other explanations to the larger share of hardware modifications is that it may be more transparent how a certain hardware problem can be resolved than it is for a software problem, or that the hardware is more problematic and thus requires more improvisation to get it working.

It appears that this case is an economically significant example of a modality of production beyond the software industry. Apart from significant adoption, levels of innovation are similar to large players in the incumbent industry, but exhibit radically higher growth rates. A heterogenous set of motivations and collaborative behaviors where reported through the survey; free revealing is dominant and open designs are frequently published to and retrieved from user developed infrastructure.

Chapter 5

Analysis and conclusions

For an individual it becomes increasingly attractive to develop physical objects through the open source development methodology. The effort expended, if judged as a cost at all, is more than offset by the benefits that it provides to that individual. The effort required from a single individual is reduced because of the ability to reuse existing components and the opportunity to collaborate and coordinate activities with others (Baldwin and von Hippel, 2009). Moreover, the tools to participate in this process are increasingly attractive and accessible to a progressively wider set of people. Innovative activities are found to be rewarding not solely because of their utility. Thus, there are several intrinsic incentives that appear to be highly motivating (see also sections 2.2.3 and 3.2).

Based on the requirements for user innovation to flourish, I conclude that open source physical production of goods is facilitated by three major factors[1]. Firstly, an individual participant's low fixed and incremental costs to design and physical production. Secondly, sufficient incentives that justify incurring said costs, if applicable. Thirdly, open collaboration as a means to spread the workload and have access to the much larger collective assets that help achieve the individual goals[2]. In the following sections we will go over each of these factors, as they relate to production of both software and physical objects.

[1]As mentioned in section 2.2.1, user innovation theory provides conditions under which this mode of innovation flourishes. (1) at least some users have sufficient incentive to innovate, (2) at least some users have an incentive to voluntary reveal information sufficient to enabled others to reproduce their innovations and (3) user self-production can compete with commercial production and distribution.

[2]Benkler (2006, p. 121) posits that technologies that lower an individual's capital cost is a condition for decentralized production to be feasible. Moreover, Kollock (1999, p. 229) points out that the kind and quantities of contributions made online will be sensitive to the costs and benefits involved – he also notes that these costs, for digitized information can be near zero. Similarly, Cheshire (2007) indicates that low cost of contributions combined with features such as jointness of supply and replication, properties that are in inherent in digitally encoded information, allow otherwise small psychological processes to create significant incentives to cooperate (see also section 2.2.4).

5.1 The costs of the tools of production and distribution

The tools required for software production are widely available and cheap, as pointed out, among others, by Lakhani and Panetta (2007, p. 106). This is consistent with the observation that a lot of development tools have been created by open source communities, often because it helped the participants in their daily work. Of the more than 230,000 projects listed on SourceForge, a popular site where open source projects can be hosted, 34,000 fall into the category ”Software development”. It contains many examples of tools that are of high quality that have gained significant prominence even in the presence of a large commercial, and initially proprietary, market. Moreover, all of the open source tools can, by definition, be distributed at no charge. Clearly, the availability of affordable, high quality development tools helps lower the barriers to software production.

After initiation of a project, collaborative production requires replication of the current state of a project and distributing the locally made changes back to the project's source code repository. Distribution and testing of the whole software product can be done at close-to-zero cost and requires no third party involvement to fix a bug (Ibid., von Hippel and von Krogh, 2006, p. 22). The private transaction costs can be low enough to justify the private benefits derived (a better product). Sharing the modification for the public benefit of others often involves minimal effort and often has some private benefits.

The design process for physical objects is increasingly digitized, thanks to increasingly powerful and affordable computer aided design (CAD) software and digital fabrication equipment such as the RepRap machine. This results in further codification of designs and lower transaction costs for replicating the results and sharing the workload. A web page with some CAD-files and instructions can suffice to enable others to replicate a result and build on it. It is important to note that the cost of replicating the innovation is not incurred by the person sharing it, but rather by the one that wishes to replicate it. This is consistent with the finding that free revealing is common for physical hardware modifications, in fact more so than for software modifications (see section 4.1.3).

Those who replicate a physical innovation from the digital design files will always incur a certain material cost. Yet, compared to the scenario where one also has to develop the design, it can be significantly time-saving to adopt pre-existing designs. Also, an existing design might already be tested by its developer and/or others. Before replicating it, some modifications may need to be made to allow it to be applied in the environment of the person who is adopting it. This results in designs being exposed to more extensive testing in a wider range of environments than the original developer could have done alone. Improvements, can be shared easily, as norms and rules may or may not require. These are important reasons to freely reveal, adopt and improve on innovations.

Because the findings from the survey show that various aspects of open and distributed innovation are on par or even higher for hardware than for software, it must be that these activities are made sufficiently easy and low-cost to justify performing them.

Collectively, potential users of an innovation already hold critical knowledge assets for the creation of innovations, because of their access to need-related and context-of-use information (Shah, 2005). Another major component is solution knowledge, which can be acquired through trial-and-error experimentation and which can be shared in a community (as demonstrated by Wikipedia). Consequently, in many cases this means that together they can innovate at a low cost. However, this requires access to prototyping tools and resources and the ability to distribute private prototyping costs among participants so that they are more than offset by the individual participants' perceived benefits.

5.1.1 Prototyping cost drivers

Prototyping 'virtually' usually doesn't involve a large monetary investment. To understand the barriers to distributed prototyping and the extent to which it may be feasible, it is of crucial importance to understand the cost-structure of physical prototyping. Physical prototyping requires an investment in physical resources, some of which are fixed costs, others incremental, such as costs per design iteration. Resources that are occasionally needed and that have a long life-time are candidates for sharing, examples are workspaces, power tools and digital fabrication equipment. Materials may be used once per iteration or reused[3]. To the extent to which customized parts cannot be recovered or recycled for further prototyping iterations these are unavoidable costs. But the amount of unrecoverable parts can be reduced through design architecture and a distributed search for ubiquitous low-cost parts. Assembly time is often at odds with modularization, so in some cases the use of unrecoverable custom parts can be a deliberate choice in order to reduce assembly time, which is another major input to manufacturing costs. Computer driven production technologies and especially 3D printing are well suited for part consolidation. While parts can be physically consolidated, they can still be produced based on a modular architecture in the CAD software. With respect to the design they are still modular, but assembly is still facilitated because of integrated assemblies. This somewhat relaxes the tension between modularization and integration. Moreover, complex, fully functional assemblies, such as a clock with gears and a pendulum, can be 3D printed in one go without requiring any human assembly or intervention (Gibson et al., 2010).

The cost of a 3D printed prototype used to be much higher than it is now. There are two ways to obtain a 3D printed prototype: through in-house rapid prototyping and through prototyping service bureaus. Having access to a RepRap significantly lowers

[3]It is perhaps of interest to note that full recycling of parts and even automated assembly and disassembly are the holy grails of physical prototyping and people within the RepRap community are working towards these goals. Apart from ecological benefits, it allows a further lowering of the costs to experiment.

the cost of physical prototypes when compared to the prints from models available from commercial vendors. It is not uncommon for people with RepRaps producing objects based on ideas that's friends provided, since the costs involved are relatively modest. This has to do with a large difference in price of both the machines and the consumables (e.g., production thermoplastics). The RepRap and most of its derivatives are sub-1000 dollar 3D printers while most commercial vendors offer such machines at a price point that is an order of a magnitude higher. Unmistakably there are differences in quality, but this does not take away the fact that the commercial vendors are mostly unwilling or unable to cater the needs of consumer markets. Similarly, the thermoplastics from commercial vendors are more expensive, because it is common that these have to be acquired from approved distributors. The client is deliberately locked-in to use these sources only. This is done through technological lock-in (in some cases with chips to verify authentic cartridges) and vendors further discourage the use of alternative consumables by stressing that this voids the warranty or will require higher service contract fees[4]. In an interview, Gerald Barnett of the University of Washington mentions that the vendors have locked materials into a high-end mode, running up the costs of doing exploratory or iterative print design and making it difficult for third parties to develop new materials. He goes on to mention that present open source equipment does not reach the high end in terms of 3D print quality, but does deliver good enough quality. He argues that good enough quality can be a more important driver than further incremental improvements in existing materials[5].

The availability of lower-cost manufacturing tools and services allow a much wider set of people to innovate. The RepRap community itself is an example of concurrent use and development of the fabrication tool. The fact that development tools are a significant part of the open source effort itself is consistent with the case of software, and allows commodification of high quality tools (developed mostly by user innovators). The rapid growth of the installed base of open source 3D printers (see section 4.1.1) lowers the barrier for people to innovate.

5.1.2 Essential function of physical prototyping

Even though developers can carry out increasingly sophisticated computer simulations, physical prototyping remains an essential part of the design process. Thomke (1998) says that simulation is beneficial to R&D because developers can increase the diversity and frequency of problem-solving cycles while reducing the total amount of time and money spent on R&D. 3D printing, which is called Rapid Prototyping for exactly this reason, is beneficial in exactly the same way. Advances in model making methods and in particular 3D printing are mentioned by Thomke et al. (1998, p. 18) as

[4]Stratasys explicitly mentions: "we attempt to protect against replication of our consumables through patents and trade secrets and we provide that our warranties are valid only if customers use consumables that we certify". From: SEC Annual Report filings. Form 10-K, Stratasys Inc., March 2010.

[5]Gerald Barnett is Director of the Research Technology Enterprise Initiative, University of Washington. The university runs a well equipped Rapid Prototyping lab where they have developed several new materials.

being responsible for a similar reduction in time and cost of a whole variety of experiments.

Still, physical prototyping results in inevitable costs associated with material expenditure as mentioned in section 5.1.1. In addition, a tangible result may be required to keep motivation high. Seeing a partially working prototype can be very exciting through a sense of achievement and comforting because private benefit may be achieved and time is well spent[6]. This achievement can be shared at relatively low communication costs (posting a picture or Youtube movie). The revealed successes may help create momentum for further development by others. If a person knows this, it is also in his or her private interest and justifies incurring prototyping costs even if it's still an early, proof-of-concept design without a direct use value. The revealed results build the participants' confidence that the collectively held goal can be achieved.

5.2 Incentives: Benefits materialize

Given the voluntary nature of the majority of the contributions, incentives other than monetary compensation are dominant. 59% of contributors to open source software projects sampled by Lakhani and Wolf (2003) report that use of the output they create is one of the three most important incentives inducing them to innovate. In other words, the private benefit from using it can be an important motivator in open source communities. This makes it important to realize that the tools to prototype can be the same tools that enable manifestation of the private benefits. Due to the evolving quality of prototyping tools, better results are acquired at low costs. For an increasingly large set of products they can be competitive manufacturing tools of the end-product. Once it is designed, the incremental costs of sharing a design online is in many cases more than offset because others provide feedback and can further develop the design[7]. Since the design is shared digitally – it is usually just a matter of uploading a file – even minor incentives can play an important role to encourage this behavior[8].

User innovators don't need to start from scratch (von Hippel, 2001, p. 82). The task granularity determines the various sizes of tasks available to individuals with a varied level of ambition[9]. One of the smaller tasks is bug fixing. The major incentive for a user to fixing or reporting a bug is that it improves his and other users' satisfaction with the product. The private benefits may be enough to justify the effort, the social benefits (praise, reputation) further justify incurring the effort to freely reveal the modification. Better integration of the fix in future versions made by others are another reason for

[6] This is frequently observed in comments posted on Thingiverse, a website that is used to share digital designs that can be 3D printed or otherwise fabricated with automated flexible manufacturing technologies.

[7] For the role of feedback, please refer to the Forward-looking Social Approval Reward Hypothesis in section 2.2.4.

[8] Cheshire (2007) concludes that the features of such a system of generalized exchange allow "otherwise small social psychological processes to have a significant impact on cooperation in generalized information exchange".

[9] The concept of task granularity was introduced by (Benkler, 2006, pp. 100–101) and refers to the size of the of smaller sized modules and the corresponding investment required to produce them.

free-revealing. This, however, is a double-edged sword: Intrinsic value of participation is at risk when there's a failure of integration of one's work into the project (Benkler, 2002). In other words, if your modification or fix is not accepted by the larger community, you might have to maintain your own local version which integrates the fix, and this version may have higher maintenance costs or will not develop further.

5.3 Collaboration: Spreading the workload

5.3.1 Collaboration and modular architectures

Digitization of the design and manufacturing process, apart from requiring less material expenditure through simulation and virtual prototyping, also encourages a modular architecture with many resulting accompanying benefits. The modular architecture that is used in the RepRap community shows striking similarities with software architectures common in open source software projects. Modularity enables multiple participants to work on separate modules independently and allows more rapid innovation by recombining modules in different ways. In open source projects, this type of module reuse is very common, as indicated in section 2.1.3.

5.3.2 Location

It is often more efficient to carry out several prototyping iterations in one physical location rather than having many disparate people each doing a single iteration. Possible reasons for this are access to physical resources that are tied to a fixed location and the concept of sticky information – the cost of transferring information from one locus to another (von Hippel, 1995). It would seem sensible to concentrate innovation in one site. But the concept of sticky information at the same time provides an explanation why in a certain locus, innovators tend to rely on local information. For this reason, geographical concentration limits the access to knowledge assets held by individuals who are not in that region. A reduced dependence on local resources increases the potential for a project to elicit contributions from a more dispersed audience. This audience has a higher average physical proximity, but potentially a much lower social proximity. Breschi and Lissoni (2001); Jeppesen and Lakhani (2010) argue that this social proximity has a significant impact on collaboration and knowledge exchange. Boudreau et al. (2008) emphasize that a "parallel search effect" benefits innovation by broadening the search for solutions, which is especially important for complex problems where just exerting high effort is not enough because these problems implicate multiple knowledge sets. Generally, the more granular and diverse the available tasks, the larger the potential pool of participants (Baldwin and Clark, 2006). Reduction in the stickiness of design information helps communities to leverage disparate pools of participants.

The survey suggests that innovation related information is frequently shared in the RepRap community, even more so for physical products than for software. Moreover, the level of collaboration and the expected ease of adoption, too, appear to be higher, even when adjusting for the relatively large share of hardware innovations. It appears that the transfer of physical resource related knowledge is greatly facilitated. The sharing of innovation related knowledge might be facilitated by having access to codified representations of the innovation. If this by itself would be sufficient, it might be reasonable to expect to see more distributed innovation communities that develop physical innovations without physically manufacturing them by themselves or having them manufactured. In section 5.2 I argue that the ability to obtain a physical representation of the digital design has private benefits and that it supports hardware innovators who participate in fully distributed collaborative innovation.

More precisely, von Hippel (1995) defines the stickiness of a given unit of information in a given instance as the incremental expenditure required to transfer that unit of information to a specified locus in a form usable by a given information seeker. This means that stickiness is influenced by aspects of the information, the available transmission media, the sender and the recipient. In the RepRap community the innovators are set up to frequently exchange bits of information, they have adopted a set of tools that facilitates the process. Similarly, tools adopted by information seekers within the community allow them to stay informed of recent development or to find highly specific information in an archive, among other things. When no suitable alternative existed, members of the community have often developed such tools.

Drivers that enable lower-cost coordination and information sharing include dedicated infrastructure that is built for this purpose, such as Thingiverse, and general purpose infrastructure such as wiki's and video sharing platforms. Hence, the development of infrastructure by participants and stakeholders in and around the community is driven, in part, by both endogenous and exogenous trends. It is reasonable to expect that technically, the sharing of physical innovations and its accompanying information will only become easier and can over time be done at a lower cost.

5.4 Conclusions

While open source software (OSS) development has been studied extensively, relatively little was known about the viability of the same development model for a physical object's design. This thesis analyzes the relevant theory related to open source software and innovation of open design in the light of new empirical evidence gathered from the RepRap project.

While the term open source is used in several ways, it has a few salient characteristics. It is usually referred to as a development methodology often practiced by communities of autonomous individuals who are geographically dispersed. Collaboration is facilitated in several ways, one of which is through its license that is used to provide freedoms rather than imposing restrictions on usage. This thesis describes the distinctive development process of open source as it is applied to software and designs of physical objects.

Open source physical design, also known as open design, differs from OSS in that it has an embodied manifestation. This has implications for dissemination of the related knowledge and the logistics of this manifestation that has lead observers to think that open design is fundamentally different.

Open design does differ from OSS in terms of the maturity of its licenses. OSS has a range of mature and popular licenses that have proved effective. Open design, by contrast, is not even clearly defined while it's development is being practiced based on software licenses that may prove to be incompatible and ineffective. However, apart from licensing, the development methodology of open source software and open design share many similarities.

Design information can be digitally encoded and transmitted much like software code. The motivation to develop or improve software may be induced partly by the ability to benefit from its use. Designing a physical object can be done for the similar reasons, benefitting from its use can result from the ability to fabricate the object. In the context of this thesis, another important similarity is that both in OSS and open design, the tools to practice open source development are often user-developed as well.

The RepRap project is existing proof that the open source development methodology also works for the design of physical objects. Development of physical subsystems of the RepRap has been done with the assistance of digital fabrication technology, performed by a large, globally dispersed group of contributors and freely revealed under an open source license.

Moreover, the creation of a large library of other open design files was been enabled by the development of platforms like Thingiverse, the availability of affordable fabrication capabilities and the willingness of communities to contribute to it. The distributed manufacturing capability allows people's designs to have a utility while the costs to share a design are very low. Both the theoretical part and the case study reveal many motives for people to share and collaborate and their good fit with the distinctive modality of open source development.

In this thesis I have argued that there are several ways in which the distributed and collaborative process of designing physical objects can be facilitated. Design information needs to be shared at low cost. It is helpful if the design can actually be fabricated, because private benefits resulting from the physical outputs may be a motive. As we have seen in the case study, the considerable adoption and development of sharing and collaboration tools and infrastructure makes these lowered costs possible. These tools include the several variants of the RepRap machines and design sharing infrastructures like Thingiverse.

The survey reveals substantial adoption and development of 3D printer technology, comparable to the larger vendors in the industry. At the rapid exponential growth of the community, doubling every 6 months, it is feasible that its adoption and levels of innovation will exceed that of the incumbent industry. Apart from thousands of modifications to the hardware development tools themselves, the tools were employed by users to develop and manufacture many thousands of other objects ranging from household items to robotics platforms. Within the community there is a higher incidence of modifications of hardware than in software, and, surprisingly, hardware modifications are expected to be relatively easier for others to replicate. The level of collaboration is also higher for hardware than for software. In the RepRap community, the creation, transfer and diffusion of open hardware does not appear to be unfavorable compared to software does not appear to restrict its viability.

This thesis shows that, with its tools, infrastructure and incentives, the RepRap community uses the open source development methodology for the design of physical objects in a highly successful and democratizing way. There are many implications of the extensibility of this phenomenon. Obtaining the digital design for a product becomes increasingly attractive compared to having to acquire the physical object. This is partly due to logistics of physical objects involving lead-times and transportation costs. It also mitigates the problem of under-provisioning, such as in markets with heterogenous demand or where the prospect of capturing rents from sales is estimated to be low, or is hard to substantiate (von Hippel and Franke, 2003).

In chapter 5, special attention is given to the role of the capability that RepRap tools provide, and their effect on the ability to collaborate. It affects the cost of development, production, reproduction and distribution of physically embodied innovations. While artifact embodied tacit knowledge influences the locus of innovation, the implications of this 'embodiedness' can be mitigated (section 5.3.2). Evidence from the survey makes this a plausible explanation for the thriving distributed activity in open design.

Chapter 6

Discussion

It appears that this case is an economically significant example of an alternative modality of production, beyond the software industry, that fundamentally inverts the use of intellectual property rights, while at the same time exhibiting increased the level of innovation based on a heterogenous set of motivations and collaborative behaviors. This stresses the need to reconsider the role of intellectual property and to identify and counter policy bias that is suboptimal in terms of provisioning of goods in society (von Hippel and Jong, 2010).

As shown in section 2.2.3, the substantial presence of intrinsically driven contributors can yield more creative results. If the open design phenomenon becomes more prominent, it could be accompanied by a more substantial share of enjoyed activities that contribute to people's quality of life. Moreover, the studied case demonstrates that these results can be effectively combined through online collaboration into a competitive system that is better-suited for these users than could be acquired in the marketplace (in this case, low-cost, tinkerer-friendly 3D printers). This means that many additional – more creative and innovative – solutions are developed than would otherwise result from market or hierarchy-based production modalities. Without a restrictive application of intellectual property rights, the output retains its public good aspects which are essential to sustaining the – highly desirable – innovation process that produced them in the first place (Henkel and von Hippel, 2004; Bessen, 2005).

With every advancement of distributed fabrication technology, the range of objects that can more efficiently be distributed in digital form expands. Obtaining a physical instance of an object from a remote third-party involves lead times, transportation, transaction, coordination and agency costs. Personal fabrication based on digital design files becomes increasingly attractive as benefits of digital distribution start to outweigh the benefits of centralized manufacturing (such as returns to scale, and a higher sophistication of equipment, etc. See also, (Reeves, 2008)). The ability to modify or tailor a design before manufacturing it can be considered an important benefit. In particular, this has already been suggested to be a trait of open source software that is considered important to users with complex needs (Bessen, 2005). The benefits of having access to source code are similar for binary code and manufactured products, when considering the ability to modify such a product. Benefits of having radically more options available may make open design a popular choice among user innovators and high-need consumers. Moreover, it would lead to a higher demand for better fabrication capabilities to leverage these benefits of open design. This study reports substantial adoption of personal fabrication technology, which further stresses the importance of a better understanding of how this could influence the evolution of supply networks in markets of physical products.

6.1 Limitations and suggestions for further research

It would be a mistake to claim that the RepRap project is a typical open source project. In open source software, Linux is one of the most frequently cited examples. It is not a typical project and it is studied frequently because it is a salient and successful example. This study, like studies of Linux, is valuable because it shows how an alternative organization of collaborative work can be viable. The performance and precise dynamics of this development methodology deserve further attention. Such a study could include multiple open hardware projects with varying degrees of performance or further longitudinal studies of a single community.

The emergence of a commons of digital designs for physical objects deserves further attention. In particular, the dynamics and conditions under which such a commons is viable and the implications for innovation policy should be further examined. Furthermore, the case study suggests that it lowers the cost for subsequent innovations. It is important to gain a better understanding of the opportunities that such a commons may create.

Licensing issues, such as the poor fit of copyright-based licenses for open design have not been resolved (Ackermann, 2009, pp. 192–193). While licenses may only play a supportive role, even potential problems could influence the perceptions and incentives of developers. Moreover, as projects become more bigger there is more at stake. In this case a more intense dispute among stakeholders can be expected. The case study shows that, even with these unresolved issues, physical design seems to be a viable domain for open source development practices. Nevertheless, the co-evolution of licensing strategies and these newly emerging types of communities deserve further attention.

The value that is generated in the community is being captured by individuals, user entrepreneur based businesses and to some extent by the original additive manufacturing market. The additive manufacturing market has been relatively stable during the recession, while the impressive growth came from sales of RepRap derived systems. Arguably, the rapid emergence and dominance of open source based entrants shows the potential of user entrepreneurship and the potential for a favorable relationship between the community and business activities. More research of the strengths and tensions between the community combined with entrepreneurial and commercial activity is warranted(as also pointed out by Muffatto, 2006, p. 227). Von Krogh and Haefliger et al. (2010) stress the need for more studies of community embedded user entrepreneurship[1]. Related research is warranted because this suggests that there is a potential for businesses to limit training costs by regarding such communities as a pool of active and skillful people (as suggested by Muffatto, 2006, p. 62). This may create opportunities for employers and and community members operating outside of the software market.

Apart from entrepreneurial activity, it seems interesting to focus on the interplay between community and incumbent industry. The case study shows that an open source community of user innovators can be a source of disruptive technology in the presence of a pre-existing industry. Players in this industry have been unable or unwilling to address the needs of the segment of user-innovators who are now increasingly able to address their own needs. Bower and Christensen (1995, p. 47) reason that incumbents fail to tap emerging markets because they tend to stay close to the center of markets they successfully serve. When lower-end products cannibalize on sales of higher-end products, it appears irrational for an organization to make the lower-end products a priority, making it hard to mobilize an organization, especially given the risks associated with making this decision based on imperfect information. In the words of Bower and Christensen, it's unlikely for companies to choose to go downmarket. Urban and von Hippel (1988) suggest to analyze lead users to gain a better understanding of future needs and even to find user-developed prototypes. Dahlander and Wallin (2006) investigate how firms can unlock communities as complementary assets to their in-house capabilities. Nevertheless, the interplay between businesses and emerging communities of user-innovators are under-researched. The evolution of the current community can serve as an important contribution to this research, since it is relatively large in relation to the incumbent industry and growing fast. Moreover, it introduces collaborative development based on free revealing of innovations into an industry that banks on intellectual property and trade secrets for their mostly competitive patterns of interaction.

[1] CIR Lecture, Tilburg University, The Netherlands, October 1, 2010. See also: (Shah and Tripsas, 2007).

Bibliography

Ackermann, J. R. (2009). Toward Open Source Hardware. *University of Dayton Law Review*, 34(2):183–222.

Allen, R. (1983). Collective invention. *Journal of Economic Behavior and Organization*, 4(1):1–24.

Amabile, T. M. (1998). How to kill creativity. *Harvard Business Review*, 76(5):76–88.

Ariely, D., Kamenica, E., and Prelec, D. (2008). Man's search for meaning: The case of legos. *Journal of Economic Behavior & Organization*, 67(3-4):671–677.

Baldwin, C. Y. and Clark, K. B. (2006). The architecture of participation: Does code architecture mitigate free riding in the open source development model? *Management Science*, 52(7):1116–1127.

Baldwin, C. Y., Hienerth, C., and Von Hippel, E. (2006). How user innovations become commercial products: A theoretical investigation and case study. *Research Policy*, 35(9):1291–1313.

Baldwin, C. Y. and von Hippel, E. (2009). User and Open Collaborative Innovation: Ascendent Economic Models.

Balka, K., Raasch, C., and Herstatt, C. (2009). Open source enters the world of atoms: A statistical analysis of open design. *First Monday*, 14(11).

Baxter, P. and Jack, S. (2008). Qualitative Case Study Methodology : Study Design and Implementation for Novice Researchers. *The Qualitative Report*, 13(4):544–559.

Behlendorf, B. (1999). *Open Source as a Business Strategy. In "Open Sources: voices from the open source revolution"*, pages 149–170. O'Reilly, Sebastopol, CA.

Benkler, Y. (2002). Coase's Penguin, or, Linux and The Nature of the Firm. *Yale Law Journal*, 112(369).

Benkler, Y. (2006). *The Wealth of Networks: How Social Production Transforms Markets And*. Yale University Press.

Bessen, J. E. (2005). Open Source Software: Free Provision Of Complex Public Goods. *SSRN Electronic Journal*, (July).

Block, J., Bock, A., and Henkel, J. (2010). Commercializing Own User Innovations Inhouse - Benefits and Challenges of Manufacturer - User Integration.

Bollinger, T., Nelson, R., Self, K. M., and Turnbull, S. J. (1999). Open-Source Methods: Peering Through the Clutter. *IEEE Software*, (July/August):8–11.

Boudreau, K. J., Lacetera, N., Lakhani, K. R., and Lydon, M. (2008). Parallel Search, Incentives and Problem Type: Revisiting the Competition and Innovation Link 1. *Technology*.

Bower, J. L. and Christensen, C. M. (1995). Disruptive technologies: Catching the wave. *Harvard Business Review*, 73(1):43–53.

Breschi, S. and Lissoni, F. (2001). Localised knowledge spillovers vs. innovative milieux: Knowledge "tacitness" reconsidered. *Knowledge Creation Diffusion Utilization*, 273:255–273.

Cheshire, C. (2007). Selective Incentives and Generalized Information Exchange. *Social Psychology Quarterly*, 70(1):82—-100.

Crowston, K. and Howison, J. (2005). The social structure of free and open source software development. *First Monday*, 10(2).

Dahlander, L. (2005). Commercializing Open Source Software: the emergence of forprofit interests in a "free" world. volume 1, page 46.

Dahlander, L. and O'Mahony, S. (2008). Progressing to the Center: The Antecedents and Consequences of Lateral Authority.

Dahlander, L. and Wallin, M. (2006). A man on the inside: Unlocking communities as complementary assets. *Research Policy*, 35(8):1243–1259.

Deci, E. L., Koestner, R., and Ryan, R. M. (Spring 2001). Extrinsic Rewards and Intrinsic Motivation in Education: Reconsidered Once Again. *Review of Educational Research*, 71(1):1–27.

Drahos, P. (2004). the regulation of public goods. *Journal of International Economic Law*, 7(2):321–339.

Ellis, T. J. and Levy, Y. (2008). Framework of Problem-Based Research : A Guide for Novice Researchers on the Development of a Research-Worthy Problem. *Informing Science*, 11.

Falk, A., Kosfeld, M., and Falk, B. A. (2005). The Hidden Costs of Control The Hidden Costs of Control. *Research in Economics*, (250).

Franke, N. and Shah, S. K. (2003). How Communities Support Innovative Activities: An Exploration of Assistance and Sharing among End-Users. *Research Policy*, 32(1):157–178.

Gacek, C., Lawrie, T., and Arief, B. (2002). The many meanings of Open Source.

Gibson, I., Rosen, D. W., Stucker, B., Gibson, I., Rosen, D. W., and Stucker, B. (2010). Design for additive manufacturing. In *Additive Manufacturing Technologies*, pages 283–316. Springer US.

Haefliger, S., Jäger, P., and von Krogh, G. (2010). Under the radar: Industry entry by user entrepreneurs. *Research Policy*, 39(9):1198–1213.

Haefliger, S., von Krogh, G., and Spaeth, S. (2008). Code Reuse in Open Source Software. *Management Science*, 54(1):180–193.

Hars, A. and Ou, S. (2001). Working for free? Motivations of participating in open source projects. In *Proceedings of the 34th Annual Hawaii International Conference on System Sciences*, page 9. IEEE Comput. Soc.

Henkel, J. and von Hippel, E. (2004). Welfare Implications of User Innovation. *The Journal of Technology Transfer*, 30(1-2):73–87.

Herstatt, C. and von Hippel, E. (1992). Developing New Product Concepts Via the Lead User Method: A Case Study in a "Low Tech" Field. *Journal of Product Innovation Management*, 9:213–221.

Hope, J. E. (2004). *Open Source Biotechnology*. Doctorate, Australian National University.

Jeppesen, L. and Lakhani, K. R. (2010). Marginality and Problem-Solving Effectiveness in Broadcast Search. *Organization Science*, (February).

Kollock, P. (1999). *The economies of online cooperation: gifts and public goods in cyberspace*. Routledge, London.

Lakhani, K. (2003). How open source software works: "free" user-to-user assistance. *Research Policy*, 32(6):923–943.

Lakhani, K. R. and Panetta, J. A. (2007). The Principles of Distributed Innovation. *Innovations: Technology, Governance, Globalization*, 2(3):97–112.

Lakhani, K. R. and Wolf, B. (2003). *Why Hackers Do What They Do: Understanding Motivation and Effort in Free/Open Source Software Projects in Perspectives on Free and Open Source Software*. MIT Press, Boston, MA.

Lather, P. (1992). Critical Inquiry in Qualitative Research: Feminist and Poststructural Perspectives: Science "After Truth". *Theory into Practice*, XXXI.

Lee, G. K. and Cole, R. (2003). From a firm-based to a community-based model of knowledge creation: The case of the Linux kernel development. *Organization Science*, 14(6):633–649.

Lessig, L. (2001). *The future of ideas : the fate of the commons in a connected world*. Random House, New York, 1st ed. edition.

Lüthje, C. (2003). Customers as Co-Inventors: An Empirical Analysis of the Antecedents of Customer-Driven Innovations in the Field of Medical Equipment. In *Proceedings from the 32th EMAC Conference*, Glasgow.

Lüthje, C. and Herstatt, C. (2006). User-innovators and "local" information: The case of mountain biking. *Research Policy*, 34(6):951–965.

Lüthje, C., Herstatt, C., and von Hippel, E. (2002). The Dominant Role of "Local" Information in the User Innovation The Case of Mountain Biking. *SSRN Electronic Journal*, pages 1–32.

Maccormack, A., Rusnak, J., and Baldwin, C. Y. (2008). Exploring the Duality between Product and Organizational Architectures: A Test of the Mirroring Hypothesis.

Mashima, R. and Takahashi, N. (2008). The emergence of generalized exchange by indirect reciprocity. In Biel, A., Eek, D., Garling, T., and Gustafsson, M., editors, *New Issues and Paradigms in Research on Social Dilemmas*, pages 159–176. Springer US.

Meyer, P. B. (2003). Episodes of Collective Invention.

Muffatto, M. (2006). *Open source: A multidisciplinary Approach. In: Series on Technology Management*. Imperial College Press, Padua, Italy.

Nuvolari, A. (2004). Collective invention during the British industrial revolution: the case of the Cornish pumping engine. *Cambridge Journal of Economics*, 28(3):99–119.

Nuvolari, A. and Rullani, F. (2007). *Curious exceptions? Open source software and "open" technology. In: Handbook of research on open source software: Technological, economic, and social perspectives.* Information Science Reference, Hershey, New York.

Osterloh, M. and Rota, S. (2007). Open source software development - Just another case of collective invention? *Research Policy*, 36(2):157–171.

Raymond, E. S. (1999). The cathedral and the bazaar. *Knowledge, Technology & Policy*, 12(3):23–49.

Reeves, P. (2008). How rapid manufacturing could transform supply chains. *Supply Chain Quarterly*, 2(04):32–336.

Robottom, I. and Hart, P. (1993). Research in environmental education: Engaging the Debate. *Deakin University Press.*

Ryan, R. M. and Deci, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *The American psychologist*, 55(1):68–78.

Shah, S. K. (2005). *Open Beyond Software*. O'Reilly Media, Sebastopol, CA.

Shah, S. K. and Tripsas, M. (2007). The accidental entrepreneur: the emergent and collective process of user entrepreneurship. *Strat. Entrepreneurship J.*, 140(November):123–140.

Shapiro, C. and Varian, H. R. (1999). *Information Rules: A Strategic Guide to the Network Economy*. Harvard Business Press; 1st edition.

Shirky, C. (2005). *Epilogue: Open Source outside the domain of software. In: Perspectives on Free and Open Source Software.* MIT Press., Cambridge, MA.

Spaeth, S., Haefliger, S., and Wallin, M. (2008). Open Source Software: What we know (and do not know) about motives to contribute.

Spaeth, S. and von Krogh, G. (2007). The open source software phenomenon: Characteristics that promote research. *Journal of Strategic Information Systems*, 16:236–253.

Stake, R. E. (1995). *The art of case study research.* Sage., Thousand Oaks, CA.

Tapscott, D. and Williams, A. D. (2008). *Wikinomics*. Atlantic Books, London, fully revi edition.

Thomke, S., von Hippel, E., and Franke, R. (1998). Modes of Experimentation: An Innovation Process and Competitive Variable. *Research Policy*, 27(3):315–332.

Thomke, S. H. (1998). Simulation, learning and r&d performance: Evidence from automotive development. *Research Policy*, 27(1):55–74.

Urban, G. L. and von Hippel, E. (1988). Lead User Analyses for the Development of New Industrial Products. *Management Science*, 34(5):569–582.

von Hippel, E. (1976). The dominant role of users in the scientific instrument innovation process. *Research Policy*, 5:212–239.

von Hippel, E. (1988a). *Shifting the Functional Source of Innovation*. Oxford University Press.

von Hippel, E. (1988b). *The sources of innovation*. Oxford University Press, New York.

von Hippel, E. (1995). "Sticky Information" and the Locus of Problem Solving: Implications for Innovation. *Management Science*, 40(4):429–439.

von Hippel, E. (2001). Innovation by User Communities: Learning from Open-Source Software. *MIT Sloan Management Review*, Summer 200:82–86.

von Hippel, E. (2005a). *Democratizing Innovation*. MIT Press, Cambridge.

von Hippel, E. (2005b). *Introduction and overview*, volume 44, chapter 1, pages 1–17. MIT Press, Cambridge.

von Hippel, E. (2006). *Innovation Communities*, chapter 7, page 93. MIT Press, Cambridge.

von Hippel, E. (2007). Horizontal innovation networks–by and for users. *Industrial and Corporate Change*, 16(2):293–315.

von Hippel, E., De Jong, J., and Flowers, S. (2010). Comparing Business and Household Sector Innovation in Consumer Products: Findings from a Representative Study in the UK. *Social Science Research Network*, (September):1–39.

von Hippel, E. and Finkelstein, S. (1979). Analysis of Innovation in Automated Clinical Chemistry Analyzers. *Science & Public Policy*, 6(1):24– 37.

von Hippel, E. and Franke, N. (2003). Satisfying Heterogeneous User Needs via Innovation Toolkits: The Case of Apache Security Software. *Research Policy*, 32(7):1199–1215.

von Hippel, E. and Jong, J. P. J. D. (2010). Open, distributed and user-centered: Towards a paradigm shift in innovation policy.

von Hippel, E. and Riggs, W. (1994). The Impact of Scientific and Commercial Values on the Sources of Scientific Instrument Innovation. *Research Policy*, 23(July):459–469.

von Hippel, E. and von Krogh, G. (2003). Open Source Software and the "Private-Collective" Innovation Model: Issues for Organization Science. *Organization Science*, 14(2):209–223.

von Hippel, E. and von Krogh, G. (2006). Free revealing and the private-collective model for innovation incentives. *R and D Management*, 36(3):295–306.

von Krogh, G., Spaeth, S., and Lakhani, K. R. (2003). Community, joining, and specialization in open source software innovation: a case study. *Research Policy*, 32(7):1217–1241.

von Krogh, G. and von Hippel, E. (2003). Special issue on open source software development. *Research Policy*, 32:1149–1157.

Weber, S. (2004). *The success of open source*. Harvard University Press, Boston.

Yin, R. K. (2002). *Case study research : design and methods*. Sage Publications, Inc, Thousand Oaks ; London ; New Delhi : Sage, 3rd edition.

Appendix A

RepRap derived 3D printers and vendors

Throughout this document I refer to the RepRap and derivatives as open source 3D printers. This appendix lists which products are included.

Because the RepRap is open source, one can easily reuse parts of the design and code to more quickly generate a variant. This process, often called forking has resulted in several derivative designs. Below these projects and their affiliation with the RepRap project are listed. There are many more vendors who do not carry their own design, for this reason they are not listed here.

Cornell University's Fab@Home

The RepRap inspired Evan Malone and Hod Lipson at Cornell University to develop Fab@Home, a personal 3D printer that deposits material from syringes. Although the operating principle of this machine is the same, most of the mechanics and software were developed independent from the RepRap project. The Fab@Home has a BSD license, whereas RepRap uses the GPL license. While the Fab@Home project was inspired by the RepRap project, it is not a RepRap derivative. The Fab@Home is a mostly open source 3D printer. Of the newest version, several of the electronics systems, PCBs and firmware are closed-source, but most of the design and new innovations that are created are freely revealed. This open source project has attracted developers from outside of Cornell University, however its development somewhat concentrates around university environments. This illustrates that while a project may have an open source license, the distributed development patterns are not guaranteed to emerge (Crowston and Howison, 2005).

Project URL: `http://www.fabathome.org/`

BitsFromBytes' RapMan

BitsFromBytes, a company in the UK started selling moulded parts for the early RepRap Darwin designs. Because of high demand and because it was labor intensive to produce these kits, BitsFromBytes designed a "flat pack" version of the Darwin. This version, resulted in the RapMan, could mostly be laser-cut, thus produced more quickly than with manual molding. Electronics were not included, and had to be sourced from various suppliers. Later, BitsFromBytes started selling full kits. In 2009 they introduced their third major version of the RapMan, a fairly robust design. In early 2010 they released the RapMan Pro. It was, however, mostly developed internally by BitsFromBytes. In April 2010 they launched the BfB 3000, a fully assembled 3D printer for 1,995 GBP. On october 6th 2010 BitsFromBytes was acquired by 3D Systems, one of the largest systems vendor in the rapid prototyping and manufacturing industry[1].

While starting out with a design based on the RepRap Darwin model, BitsFromBytes have created their own design files and have not been releasing their designs on a frequent basis. Nor are they fully involving the community in the design process. For this reason, recent RapMan versions cannot be said to be open source 3D printers.

Company URL: `http://www.bitsfrombytes.com/`

Evil Mad Scientists' CandyFab

Evil Mad Scientists developed the CandyFab 6000. Diffusion of these machines has not been reported. It contains a lot of independently developed tools and systems. It is unclear whether aspects of the system were inspired by the RepRap project.

Project URL: `http://www.candyfab.org/`

Makerbot Industries' Cupcake CNC

Makerbot Industries shipped a first batch of their Cupcake CNC in April 2009[2]. By the end of 2009 they had shipped nearly 500 complete kits. They have been working hard to ramp up production in order to keep up with demand. After operating for a year they had sold about 1000 kits in April 2010. The RepRap community and Makerbot industries have a close relationship, due to the people involved and their adherence to open source practices. Zach Smith, one of the co-founders of Makerbot Industries has been a very active participant in the RepRap community almost since 2006. Makerbot's second machine, the Thing-O-Matic, is expected to be released in November 2010 and supersedes the Cupcake CNC model.

Company URL: `http://www.makerbot.com/`

[1] For the concerning press release, see: `http://www.stockmarketsreview.com/news/44284/`.
[2] Source: http://blog.makerbot.com/2009/04/16/how-to-ship-makerbots/

Ultimaker's Protobox

The Ultimaker Protobox originated out of a RepRap workshop at a FabLab in Utrecht, the Netherlands. The aim was to make the machine easier to build. It is assembled from traditionally manufactured plywood sheets that are digitally laser-cut. The machine is currently in a stage just before it is going to be sold. The design for the Ultimaker is released under an open source license.

Project URL: `http://www.ultimaker.com/`

This list is not exhaustive and may be expanded further.

Appendix B

Estimation of the RepRap community size

The total population estimates of the RepRap community are derived from the sample size, the growth rate (determined through non-linear regression fitting) and estimates of the fraction of the population that was sampled. The result is a lower estimate of 3872 people and a higher estimate of 4840 people in the community in October 2010. This appendix explains how I arrived at my estimates.

Equation (B.3) can be used to forecast any population growth that is exponential, such as the RepRap population. The actual growth rate was determined from the data from the survey, where people indicated when they joined the community. Using a non-linear least squares fit (Levenberg-Marquardt nonlinear regression) on this data yields the growth model (see (B.1))[1]. This is the exponential model that best fits the survey data. The use of the Levenberg-Marquardt algorithm is a popular choice because it functions robustly across many generic curve-fitting problems.

$$a + be^{\tau/c} = 5.001016931766 + 0.023060557072e^{\tau/0.724082906028} \tag{B.1}$$

Where Tau (τ) is used as the passage of time in years. The doubling time of 6.03 months was arrived at as follows:

$$\begin{aligned} e^{\tau/0.724083} &= 2 \\ \tau/0.724083 &= \ln(2) \\ \tau &= \ln(2) * 0.724083 \\ \tau = 0.501896 \text{ years} &= 0.501896 * 12 \text{ months} \\ \tau &= 0.6022752 \text{ months} \end{aligned} \tag{B.2}$$

To go from a sample size to the population size, the response rate (r) is used. Equa-

[1] Using this implementation of Levenberg-Marquardt: `http://octave.sourceforge.net/optim/function/leasqr.html`.

tion (B.3) is applied in equation (B.4) to get the estimate for the October 2010 population.

$$N_{t=x} = \frac{n}{r} g^x \tag{B.3}$$

Where:

N is the population size ($N = \frac{n}{r}$).

$N_{t=x}$ is the population size at time $t = x$, where x is the number of months since March 2010 ($t = 0$).

n is the sample size. It equals 386 full responses.

r is the response rate. More precisely, it is the fraction of the population that the sample covers. As a lower estimate we will use 0.25, meaning that 25% of the community is covered. As a higher estimate we will use $r = 0.20$. For justification of these values, see below.

g is the monthly growth rate. Over the 5 years of data points it was determined to be 1.1218 ($\approx 2^{1/6.03}$). Note that this may yield conservative estimates because the growth rate itself appear to grown over time (see table 4.1).

This means that for October 2010 ($t = 8$) we have:

$$\begin{aligned} N_{t=8} &= \frac{386}{0.25} * 1.1218^8 \approx 3872 \text{ participants (lower estimate)} \\ N_{t=8} &= \frac{386}{0.20} * 1.1218^8 \approx 4840 \text{ participants (higher estimate)} \end{aligned} \tag{B.4}$$

In March 640 Makerbots were shipped and 10 Makerbots were built from scratch, so in total, there were 650 Makerbots in March 2010[2]. The actual number of operators may deviate slightly from this number, as sometimes a Makerbot will be owned by multiple people, possibly compensated by to some extent by people who will own multiple Makerbots. The proportion of Makerbot operators (building or finished) in the sample is 39% (151 of 386). If the Makerbot population was similarly engaged in filling in the form, this data would indicate that the response rate (r) is close to: $\frac{151}{650} = 0.232$, yielding about 1663 people in March ($\frac{386}{0.232}$). It is expected the number of people with Makerbots were more likely to be overrepresented than underrepresented because of their seemingly high willingness to participate and re-broadcast the survey among peers. If the amount of people with Makerbots is overrepresented, the response rate of 0.232 is in reality lower, corresponding to a larger community. Members of the RepRap community are asked to put their pin on the RepRap World map. This map exists for more than a year. In the survey, people were asked to indicated whether they were listed on this map of which the population was known. Before the survey, the map listed 322 people (after removing 17 duplicate entries). In the survey, 99 people

[2] These numbers were published by Makerbot Industries.

indicated they were on the world map and 281 indicated that they were not on it. was listed. During the survey the rate at which people registered on the world map did not increase, so the presence of the survey did not influence it. At the end of the survey 360 people were listed on the map. Based on the listing rate of 26%, we can infer that the amount of people in the community at the end of the survey was $\frac{360}{0.26} \approx 1385$. This indicates that r should be close to 0.28 ($\frac{386}{1385}$). It can be expected that people who respond to a request to add their pin on the map are also more likely to participate in the survey. This suggests that a response rate of 0.28 would be artificially high. Based on the above, a value between 0.2 and 0.25 is deemed a realistic estimate of the response rate.

Appendix C

List of community innovation types

This section contains categories of innovations that were identified in the RepRap project and one or more examples per category.

Type of improvement	**Example(s) from the RepRap case study**
Added functionality	• The ability to function in subtractive as well as additive operating modes (e.g., Hydra-MMM). The ability to mix multiple materials. Use of ceramics and pastes instead of thermoplastics. • Embedding wire and conductive materials.
Improved existing functionality	• Faster, more efficient, more detailed and/or stronger output.
Increased ease of assembly and use	• Derivative designs such as RepRap Mendel, Makerbot and Ultimaker Protobox.
Lower cost	• Design of an alternative belt drive mechanism. • Allowing the use of cheap roller-skate bearings

Type of improvement	Example(s) from the RepRap case study
More suitable components (e.g. easier-to-acquire)	• A drive system based on ubiquitous ball-chains as an alternative to industrial timing belt and pulleys. • The Sanguino was developed as an alternative to the Arduino.
Specialization towards a certain application	• Digital pottery system • Plant growth modeling device
Interoperability with other systems	• Compatibility with G-Code common in industrial CNC installations. • Writing platform independent software. • Adding USB interfaces and having the machine work independently from removable storage media.
Improved design architecture (e.g. modularization, part consolidation)	• Adoption of industrial standards for NC-machine control. • Change from multiple independent microcontroller in a token ring to a single master microcontroller architecture with an optional slave extruder controller.
Refining operating techniques	• Sharing better settings for making parts easier to separate from their support structure (if applicable)
Improved sharing infrastructure	• Thingiverse.com was developed as website to facilitate sharing of digital designs for physical objects and currently hosts over 3000 user contributed objects which include, documentation, discussions and the data to manufacture them or make derivative designs. • Adoption of Wiki's and blogs for knowledge sharing. • Local user groups

Appendix D

Community Survey

Note that the actual survey was administered via the web as web-based forms, hence there is a difference in appearance from this appendix.

Survey of RepRap and Makerbot Community Members

script for internet survey

- Erik, Jeroen and Eric -
version 23 February 2010

Preface

- This survey is about your motives and efforts to use and further develop the RepRap, or any derivate machine (e.g., Makerbot). We want to better understand conditions under which open development of physical products works. We also want to learn how it differs from proprietary modes of development.
- It is part of a research program initiated by the MIT Sloan school of management, (Cambridge, USA) and Tilburg University (the Netherlands) to study open innovation by online communities. I will use the data to write my master thesis.
- On average, the survey will take 15 to 20 minutes.
- All information received will remain ANONYMOUS and be treated strictly CONFIDENTIAL.
- Do you have any questions or comments? Please contact me at: phone +31(0)137113076, e-mail info@erikdebruijn.nl.
- Many thanks for your co-operation!

Best wishes,

Erik de Bruijn

SECTION A: TYPE OF USER

Intro1

The first questions are about the kind of machine(s) that you use and/or are building.

A1

Please mark what kind of machine(s) you currently use or are building.
(Multiple answers possible)

		I am having one in operation	I am currently building one
a.	Bits From Bytes Rep(st)Rap v 3.0 (acrylic)	❑	❑
b.	Bits From Bytes Rep(st)Rap v 2.0 (acrylic)	❑	❑
c.	Bits From Bytes Rep(st)Rap (earlier version)	❑	❑
d.	RepRap Darwin (built from RP parts)	❑	❑
e.	RepRap Mendel (built from RP parts)	❑	❑
f.	Makerbot	❑	❑
g.	McWire RepStrap	❑	❑
h.	Other RepStrap	❑	❑
i.	My own RepStrap/3D printer design	❑	❑

j.	Existing CNC-Mill with RepRap extruder toolhead (or using an off-the-shelf cartesian bot)	❑	❑
k.	Other machine	❑	❑

A2
When did you start building your first machine?
. . . . (month) . . . . (year)

A3
Do you have or build your own machine, or do you share one with others?
(Multiple answers possible)
❑ I have my own machine
❑ I am sharing a machine with others

A4 (if A3=2)
With how many others do you share your machine?
. . . . . .others

If A1a-A1k are only 'currently building one' then Go to A6

A5
Please mark how often you engage in the following activities.

		never	barely	sometimes	often	always
a.	Building the machine; getting it to work	❑	❑	❑	❑	❑
b.	Using a machine to print objects for yourself (e.g., rapid prototyping, direct part production, presentation models, etc)	❑	❑	❑	❑	❑
c.	Developing improvements for the machine (e.g., hardware, software)	❑	❑	❑	❑	❑
d.	Helping other users (e.g., technical assistance, sending parts, documenting your work on the Web, etc)?	❑	❑	❑	❑	❑
e.	Improving your skills (e.g., learning electronics to better work with and/or improve the machine).	❑	❑	❑	❑	❑

A6
How much time do you weekly spend on working with or developing your machine?
(please estimate - including everything, e.g. all invested time to build, use and improve the machine, and or help other users)
. . . . . .hours per week

A7 (if A6>0)
How is this time distributed across. . .

a.	Building the machine; getting it to work?	…..
b.	Printing objects?	…..
c.	Developing improvements for the machine (in order to print what I need)?	…..
d.	Developing improvements for the machine (just to make it better)?	
e.	Helping other users (e.g., technical assistance, sending parts, documenting your work on the Web, etc)?	…..
f.	Improving your skills?	…..
		100%

A8 (if A7d > 0)
How do you help other users (multiple answers possible)?
❑ By meeting people to provide technical assistance or advice
❑ By giving instructions or answering questions via the Web, e-mail or phone
❑ By sending tool or parts
❑ By posting information on the Web
❑ By improving or extending information on the Web
❑ Other, please specify………………..

A9
How much money did you spend on the machine since you started with it?
(please estimate – if your local currency is unavailable, please convert to Euros or US dollars)
………..Euros/dollars/yen/UK pounds

A11
In the past three months, how many other users of 3D printers did you communicate with? (personal communication by means of e-mail, telephone, face to face, etc – please estimate)
….users

A12 (if A11>0)
And in the past three months, how many other users did you meet in person?
….users

A13
Are you member of a local community of 3D printer users, i.e. that you meet in person from time to time?
❑ yes
❑ no

A14 (if A13=yes)
How many members does this local community have?
….members

A15 (if A13=yes)
Does this local community have a Web presence (e.g., website, wiki, blog)?
❑ yes
❑ no

A16 (if A15=yes)
Can you give us the URL of your local community's website?
. . . .

A17
What motivates you to use or build your machine? Please distribute 100 points according to what you find most important.

a.	Building the machine; getting it to work	. . . ..
b.	Printing objects	. . . ..
c.	Developing improvements for the machine (in order to print what I need)	. . . ..
d.	Developing improvements for the machine (just to make it better)	
e.	Helping other users (e.g., technical assistance, sending parts, documenting your work on the Web, etc)	. . . ..
f.	Improving your skills	. . . ..
		100%

A18 (if A17f $>$ 0)
What other reasons do you have to use or build the machine?
. . . .
. . . .

SECTION B: ADOPTING THE MACHINE

Intro2
The following questions are about the first machine that you built (or are still building).

B1
How long did it take you (so far) to get this machine working?
. . . .hours/days/weeks/months

B2
Did you face any problems to get this machine working?
❑ yes
❑ no

B3 (if B2 = yes)
Where these problems primarily related to the hardware, the software, or both?
❑ hardware
❑ software
❑ both hardware and software

B4 (if B3=1 or 3)
What sources did you consult to learn about any hardware-related problems?
(multiple answers possible)
❑ Online wiki's, forums and blogs (e.g., RepRap site, BfB, Makerbot)

❑ Online video sharing sites (e.g., Youtube)
❑ Personal communication with other users (e-mailing, chatting, telephone calls)
❑ Personal assistance by other users (clubs, one-to-one visits)
❑ Physical inspections of other machines
❑ Other, please specify..................

B5 (if B3 = 1 or 3)
Did you manage to solve your hardware-related problems?
❑ yes, completely
❑ yes, partially
❑ no or not yet

B6 (if B3=2 or 3)
What sources did you consult to learn about any software-related problems? (multiple answers possible)
❑ Online wiki's, forums and blogs (e.g., RepRap site, BfB, Makerbot)
❑ Online video sharing sites (e.g., Youtube)
❑ Personal communication with other users (e-mailing, chatting, telephone calls)
❑ Personal assistance by other users (clubs, one-to-one visits)
❑ Physical inspections of other machines
❑ Other, please specify..................

B7 (if B3 = 2 or 3)
Did you manage to solve your software-related problems?
❑ yes, completely
❑ yes, partially
❑ no or not yet

SECTION C: INNOVATING THE SOFTWARE

Intro3
The following questions relate to any software that you may develop or improve for the machine.

C1
Did you ever modify or develop any NEW software for the machine? (by programming original code)
❑ Yes
❑ No

If C1=no Go to Intro4

C2
Please describe your most important software modification/creation.
....
....

C3
The next questions are concerned with this specific piece of software.
Please mark if the following statements are true. This software... (multiple answers possible)

❑ . . . added new functions to the machine.

❑ . . . improved the convenience of the machine.

❑ . . . increased the performance of the machine (e.g., speed, resolution).

C3a
Were you the first to modify or develop this software? I think that. . . (Please mark)
❑ . . . I was first
❑ . . . others were developing/modifying similar things

C4
What motivated you to develop this software? Please distribute 100 points according to what motivated you most.

a.	I needed this software to build the machine, i.e. to get it to work	. . . ..
b.	I needed it to print specific objects	. . . ..
c.	I enjoy developing improvements for the machine	. . . ..
d.	I wanted to help other users	. . . ..
e.	I wanted to improve my skills	. . . ..
f.	Any other reason	. . . ..
		100%

C5 (if C4f > 0)
For what other reasons did you develop this software?
. . . .
. . . .

C6
What or who did you consult to develop this software?
(multiple answers possible)
❑ Online wiki's, forums and blogs (e.g., RepRap site, BfB, Makerbot)
❑ Online video sharing sites (e.g., Youtube)
❑ Personal communication with other users (e-mailing, chatting, telephone calls)
❑ Personal assistance by other users (clubs, one-to-one visits)
❑ Physical inspections of other machines
❑ Other, please specify. . . . .

C7
Did you collaborate with other users to develop this software?
❑ yes
❑ no

C8 (if C7=yes)
Can you estimate how many others were involved?
. . . ..other users

C9 (if C7=yes AND A13=yes)
Were these collaborators members of your local community?

❏ yes
❏ partially
❏ no

C10
Can you estimate how much time you spent on developing/modifying this software?
(Please estimate)
..........hours/days/weeks/months

C11
Did you spend any money to develop this software?
❏ yes
❏ no

C12 (if C11=yes)
Can you estimate how much?
(Please estimate – if your local currency is unavailable, please convert to Euros or US dollars)
.........UK Pounds/dollars/yen/euros/ etc

C13
Did you reveal the details of this software to other people?
❏ yes
❏ no

C14 (if C13=yes)
How did you reveal it? (multiple answers possible)
❏ Freely revealed it on the Web (e.g., Wiki, Forum, Blog)
❏ Selectively revealed it to specific other users (e.g., e-mail, messaging, etc)
❏ Otherwise, please specify..................

C15 (if C13=yes)
To the best of your knowledge, have any other persons adopted this software?
❏ Yes
❏ No

C16 (if C15=yes AND A13=yes)
Are these persons all from your local community?
❏ Yes
❏ No, also people outside my local community adopted it

C17
In general, what would keep other people from adopting this software?
(multiple answers possible)
❏ It is specific to my needs, not very useful to others
❏ It is still very experimental, i.e. needs further development
❏ Others find it hard to see the benefit
❏ It takes a lot of time to make it work
❏ It is hard to properly communicate, i.e. to explain how it should be done
❏ It is expensive, i.e. requires a great deal of investment
❏ It is difficult to integrate with other parts of the machine

❑ Other, please specify. . . . .
❑ None of these, it is easy to adopt this software

SECTION D: INNOVATING THE HARDWARE

Intro4
The following questions relate to any hardware that you may develop or improve for the machine.

D1
Did you ever modify or develop any NEW hardware for the machine?
❑ Yes
❑ No

Skip
If D1=no
Go to E1

D2
Please describe your most important hardware modification or creation.
. . . .
. . . .

D3
The next questions are concerned with this specific piece of hardware.
Please mark if the following statements are true. This hardware. . . (multiple answers possible)

❑ . . . added new functions to the machine.
❑ . . . improved the convenience of the machine.
❑ . . . increased the performance of the machine (e.g., speed, resolution).

D3a
Were you the first to modify or develop this hardware? I think that. . . (Please mark)
❑ . . . I was first
❑ . . . others were developing/modifying similar things

D4
What motivated you to develop this hardware? Please distribute 100 points according to what motivated you most.

a.	I needed this hardware to build the machine, i.e. to get it to work	. . . ..
b.	I needed it to print specific objects	. . . ..
c.	I enjoy developing improvements for the machine	. . . ..
d.	I wanted to help other users	. . . ..

e.	I wanted to improve my skills	…..
f.	Any other reason	…..
		100%

D5 (if D4f > 0)
For what other reasons did you develop this hardware?
……………………………………………………………………………………………
……………………………………………………………………………………………

D6
What or who did you consult to develop this hardware?
(multiple answers possible)
❑ Online wiki's, forums and blogs (e.g., RepRap site, BfB, Makerbot)
❑ Online video sharing sites (e.g., Youtube)
❑ Personal communication with other users (e-mailing, chatting, telephone calls)
❑ Personal assistance by other users (clubs, one-to-one visits)
❑ Physical inspections of other machines
❑ Other, please specify………………

D7
Did you collaborate with other users to develop this hardware?
❑ yes
❑ no

D8 (if D7=yes)
Can you estimate how many others were involved?
…..other users

D9 (if D7=yes AND A13=yes)
Were these collaborators members of your local community?
❑ yes
❑ partially
❑ no

D10
Can you estimate how much time you spent on modifying/developing this hardware?
(Please estimate)
………..hours/days/weeks/months

D11
Did you spend any money to develop or modify this hardware?
❑ yes
❑ no

D12 (if D11=yes)
Can you estimate how much?
(Please estimate – if your local currency is unavailable, please convert to Euros or US dollars)
………UK Pounds/dollars/yen/euros/ etc

D13
Did you reveal the details of this hardware to other people?
❑ yes
❑ no

D14 (if D13=yes)
How did you reveal it? (multiple answers possible)
❑ Freely revealed it on the Web (e.g., Wiki, Forum, Blog)
❑ Selectively revealed it to specific other users (e.g., e-mail, messaging, etc)
❑ Otherwise, please specify. . . . .

D15 (if D13=yes)
To the best of your knowledge, have any other persons adopted this software?
❑ Yes
❑ No

D16 (if D15=yes AND A13=yes)
Are these persons all from your local community?
❑ Yes
❑ No, also people outside my local community adopted it

D17
In general, what would keep other people from adopting this hardware?
(multiple answers possible)
❑ It is specific to my needs, not very useful to others
❑ It is still very experimental, i.e. needs further development
❑ Others find it hard to see the benefit
❑ It takes a lot of time to make it work
❑ It is hard to properly communicate, i.e. to explain how it should be done
❑ It is expensive, i.e. requires a great deal of investment
❑ It is difficult to integrate with other parts of the machine
❑ None of these, it is quit easy to adopt this hardware
❑ Other, please specify. . . . .
❑ None of these, it is easy to adopt this hardware

SECTION E: THINGIVERSE

E1
Did you ever print something that you downloaded from Thingiverse?
❑ Yes
❑ No
E2 (if E1=yes)
How many objects have you printed that you got from Thingiverse? (please estimate)
. . . . objects

E3 (if E2>0)
For how many of these printed objects have you uploaded a picture on Thingiverse? (please estimate)

.........objects

E4
Have you ever digitally designed your own physical objects?
❏ Yes
❏ No
E5 (if E4=yes)
How many designs did you make? (please estimate)
.........designs

E6 (if E4=yes)
How many of these designs did you post on Thingiverse? (please estimate)
.........designs

SECTION F: DEMOGRAPHY AND GENERAL QUESTIONS

Intro5
Finally, we would like you to answer some general questions.

F3
What is your age?
....years

F4
Are you currently employed, self-employed, a student, retired or not working?
❏ employed
❏ self-employed
❏ student
❏ retired/not working
❏ other, please specify........

F5 (if F4 = employed or self-employed)
Please describe you job or kind of business that you are in.
....
....

F6 (if F4 = student)
What kind of study do you do (e.g., engineering, information technology, business administration, etc)
....
....

F7
What is your highest educational attainment?
❏ high school
❏ bachelor degree
❏ master degree
❏ doctorate degree
❏ other, please specify..............

F10

How do you assess your skills in the following field of interest? Please mark your level of expertise.

	My level of expertise in ... is...	rookie	novice	skilled	expert
a.	programming original software code	❑	❑	❑	❑
b.	tinkering with electronics	❑	❑	❑	❑
c.	mechanical systems/machines	❑	❑	❑	❑
d.	CAD software	❑	❑	❑	❑
e.	CAM, CNC, RP systems and/or tooling	❑	❑	❑	❑
f.	design	❑	❑	❑	❑

F11
Are you currently listed on the RepRap Worldmap? (NOT the Makerbot Map)
❑ Yes
❑ No

F12
Would you like to be notified of our research findings?
(We will send our research report to your e-mail address)
❑ Yes, send the report to .... (e-mail address)
❑ No, thanks

F13
We would like to invite more users of the RepRap (or derivative machines) to take this survey. Can you give us the details (name and e-mail adresses) of three other users?

(we will carefully check that no-one is invited twice – all details will be treated confidentially and destroyed after our research)
❑ Yes
❑ No, I would rather not give such details

F14 (als F13=yes)
Please give us the details of up to three more users.
name e-mail
….. …..
….. …..
….. …..

End
This is the end of the survey. Many thanks for your co-operation.