First Monday, Volume 14, Number 11 - 2 November 2009

first monday
PEER-REVIEWED JOURNAL ON THE INTERNET

Open source enters the world of atoms: A statistical analysis of open design

by Kerstin Balka, Christina Raasch, and Cornelius Herstatt

Abstract

Extensive research has been done to analyze the phenomenon of open source software development from various perspectives. By contrast little is known about open source development of tangible objects, so–called open design, so far. Until recently, limitations to the availability of successful empirical examples of this 'new innovation model' outside software may have been a key reason for this gap.

This paper contributes to the literature on the open source mode of product development by providing a quantitative study (N = 85) of open design projects. Our goal is to explore the landscape of open source development in the world of atoms, to analyze project characteristics, structures, and success, and to investigate similarities and dissimilarities to open source software development.

Contents

Introduction

A striking phenomenon in recent years has been the rise of open source software (OSS). Source codes are freely revealed via the Internet, allowing geographically distributed programmers to download and utilize the software, to suggest improvements to the community, or to make modifications themselves and to redistribute their modified code. A large number of successful examples of open source software programs have been developed and extensive research has been undertaken to analyze this phenomenon from different perspectives (von Krogh and von Hippel, 2006).

In view of the success of OSS, experts from academia and practice suggest a broader applicability of the 'open source model' of product development outside the software industry. To date, however very few studies have been conducted in fields other than software. They mostly focus on open content, as exemplified by *Wikipedia* (Royal and Kapila, 2009), but there are hardly any studies on the open development of physical products, so–called open design.

While research on OSS provides some insights for industries beyond software, Dahlander and Magnusson (2008) point out that 'there is a wider need to understand how communities outside the hierarchical control of managers can be used in an effective manner' in other settings [1]. Physical, as opposed to purely digital, products are often regarded as less suited to the open source mode of product development as known from OSS (Hippel and Krogh, 2003).

In order to investigate this claim we choose open design as our research field, expecting to find similarities as well as differences in project attributes: We explore the open design landscape, analyze the characteristics and structures of projects, study the performance of the open design model in practical applications, and draw comparisons to OSS development. Because of the dearth of prior research we deliberately pursue this broad approach to the phenomenon of open design in order to offer an empirical foundation for future studies.

The paper is structured as follows: In the next section, we discuss the open source innovation framework and derive hypotheses on the relation between certain project characteristics and project advancement from the literature on OSS for application on open design. The third section describes our research design and data acquisition. The fourth section presents the findings organized along the open source innovation framework, and the fifth section discusses those findings and their implications in relation to the hypotheses. Finally, we conclude the paper and outline implications for future research.

Theoretical background

Open source beyond software

Open source (OS) is a methodology of product development, a 'new innovation model' (Osterloh and Rota, 2007). The term originates from the software industry and denotes the free revelation of the source code. Open source development is an example of the private collective model (Hippel and Krogh, 2003) and a form of open technology (Nuvolari and Rullani, 2007). Shah (2005) considers OSS development as perhaps the most prominent example of the 'community–based model', which extends well beyond the domain of software.

In view of the success of this model in the software industry, an increasing number of experts from academia and practice (*e.g.*, Raymond, 1999a; Lerner and Tirole, 2004) suggest its broader applicability outside the software industry. As confirmation they refer to a small number of existing projects, *e.g.*, biotechnology projects or the OScar Project (http://www.theoscarproject.org/) (Hope, 2007; Mueller–Seitz and Reger, 2008).

To generalize the 'OS model' to a non–industry specific level, we build on the concept of 'Open Source Innovation', as defined by Raasch, *et al.* (2009a): Open source innovation is characterized by free revealing of information on a new design with the intention of collaborative development of a single design or a limited number of related designs for market or non–market exploitation.

According to this definition open source innovation is characterized by a non–market, non–contractual transfer of knowledge among actors, sharing relevant information with a non–definite set of other actors without any immediate recompense. Actors share their ideas with the clear purpose of contributing to a joint development. Revealing of design information in order to gain reputation, build social status or other motives, without the understanding that this design is part of a larger design task, shall not be considered as open source innovation. The outcome is exploited, either for–profit or not–for–profit or both. The design can be produced and sold on a market, integrated into other products that are marketed, or deployed during the development of such products.Within the phenomenon of open source innovation, a distinction has to be drawn between intangible and tangible objects of development. In the non–physical world beyond software, so–called open content is currently attracting considerable attention. Examples as the entire family of wikis, open science, educational materials, cultural goods such as music or films, geographic maps (the OpenStreetMap Project at http://www.openstreetmap.org/), and other applications suggest that open content is a viable model and offers sustainable business opportunities to companies (Parker and van Alstyne, 2005).

In the realm of tangible goods, open design (OD) refers to the open development of physical objects. While much of the development work in this domain can be accomplished virtually, the ultimate purpose is the design and production of a physical artifact. Examples of open design range from beer to cars and from manufacturing equipment to IT hardware. Most of these projects are still in development; yet many have marketed semi–final products or fully functional intermediate versions for several years.

As ‘hardware is becoming much more like software’ (von Hippel in Thompson, 2008), it is important to point out that the border between open development of tangible and intangible objects is not always as clear–cut as it might appear. OSS is constituted by the sharing of instructions that will be interpreted by a computer. Similarly, open design is based on developing and sharing designs and instructions to create physical objects (Smith, 2008). According to Shirky (2007), ‘An increasing number of physical activities are becoming so data–centric that the physical aspects are simply executional steps at the end of a chain of digital manipulation’.

This paper focuses on open design rather than open content, and draws comparisons between open source development of tangible objects on the one hand and software on the other. For our empirical exploration we will use a conceptual framework proposed in Raasch, *et al.* (2009b). Its encompassing approach is most suited to grant a clear structure to our analysis guiding us through the various characteristics of open source innovation projects [2].

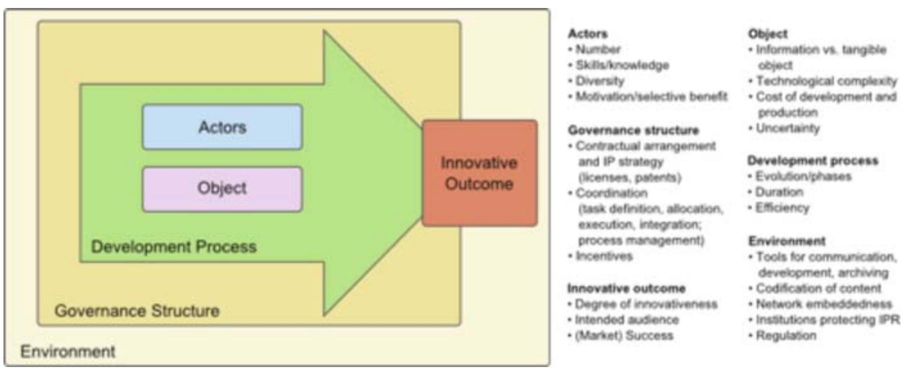

Figure 1: The open source innovation framework.

According to this framework (Figure 1), actors, in a broader sense, including investors, manufacturers, etc., collaborate within a development process. They work towards a design of an object and finally come up with an innovative solution. A suitable governance structure framing the development is devised and possibly adapted across the evolution of the development to organize collaboration and provide required institutional arrangements. The object, given its inherent characteristics, can pose requirements to actors, development process and governance structure, whereas the latter are in turn actively shaped by the actors. The constitution of the governance structure can back–propagate to the group of actors, causing self-selection and affecting their effort, and to the development process, influencing its evolution and efficiency. Finally each project operates within a technical, social, economical and legal setting surrounding the development.

Empirical studies of open source software

A large number of successful examples of open source software programs have been developed and extensive research has been undertaken to analyze this phenomenon from different perspectives (for an overview see von Krogh and von Hippel, 2006).

Large–scale descriptive statistics visualizing the variety of projects are provided by Weiss (2005). He used the easy accessibility of high volumes of information about open source software from Sourceforge, a well–known repository currently hosting about 150,000 projects.

The same data source is used by Comino, *et al.* (2007) who analyze the relationships between the various characteristics of OSS projects and model their influence on project success. Based on similar data sets obtained from Sourceforge, among others, Crowston and Scozzi (2002) identify and test factors that are important for the success of OSS projects. Healy and Schussman (2003) analyze patterns in the overall structure of OSS development communities by comparing projects using different activity measures.

Despite the high number of OSS projects listed, little research has been conducted which empirically analyzed factors determining project success. On the basis of the findings available we will now compile five hypotheses for the constituents of the open source innovation framework. The hypotheses will be used to compare previous findings from OSS to our own empirical findings in the area of open design. With the scope of the present paper we cannot cover all aspects in detail and need to focus on certain characteristics. More precisely, we will focus on aspects, which previously have been investigated in empirical studies on OSS.

(1) Actors: For OSS, Raymond (1999b) predicted and Comino, *et al.* (2007) proved empirically that the size of the community has a positive impact on project development status. Concerning the type of actors, Healy and Schussman (2003) observe that 'successful OSS projects are most often staffed by professional software developers' and 'are (more often than not) run by professionals.' [3]

For industries other than software a sufficient number of contributing developers with the required skills is likewise described as a precondition for open development to be feasible (*e.g.*, Shah, 2005). With regard to the actors involved in open design, we thus arrive at two hypotheses:

> *H1: The size of the community is positively correlated with project advancement.*
>
> *H2: The participation of commercial contributors is positively correlated with project advancement.*

(2) Object: Many researchers agree that open development today is more easily applied to information goods rather than tangible objects (*e.g.*, Hippel and Krogh, 2003). Due to the dissimilarity of the objects and its characteristics, we cannot directly apply findings from OSS and hence refrain from formulating hypothesis for this constituent.

(3) Governance structure: Demil and Lecocq (2005) describe 'the OS model' as 'a generic structure regulating transactions which could be employed in different industries'. They frame governance in the dimensions of control, incentives and a contractual framework. As a fundamental attribute of open source we focus on the contractual framework, *i.e.*, the license regulating the revelation and use or re–use of developed knowledge.

OS licenses are usually classified according to the restrictions they impose on derivative works (Bonaccorsi and Rossi, 2003). Investigating the implications of the choice of a specific licensing model Comino, *et al.* (2007) show that projects distributed under highly restrictive regulations are less likely to reach an advanced stage of development. It could be assumed that this relation also holds for open design projects, as the licensing models are very similar:

> *H3: Highly restrictive licenses are negatively correlated with project advancement.*

(4) Development process: Research on the OSS development process, its stages and efficiency is still in its infancy (Lee and Cole, 2003). In particular we miss empirical studies on OSS development processes based on which to draw comparisons to open design. In one study Crowston and Scozzi (2002) find that OSS projects with higher activity are in a more advanced stage of development. Therefore, we restrain our hypothesis in this category to the intensity of the cooperation and propose for open design:

> *H4: Activity is positively correlated with project advancement.*

(5) Innovative outcome: Studies show that relevant reasons for contributing to an OS project are related to the desire of learning and performance improvement (Rossi, 2004). Sophisticated applications targeted towards an advanced audience may on average offer more learning opportunities to the individual contributor than projects addressing end users directly. Accordingly they may have a higher likelihood of receiving substantial contributions from developers.

In the field of OSS Comino, *et al.* (2007) show that those applications are indeed more likely to reach an advanced stage of development. Therefore, we will study for open design whether:

H5: Addressing an advanced audience is positively correlated with project advancement.

(6) Environment: Several environmental factors have been found to support or hinder open development: One particular precondition for the feasibility of OSS development is the existence of strong supporting tools, in particular the Internet, that are easily accessible to the developer community at low cost. In our analysis we study the use of different tools for communication in open design communities. However due to the wide scope of environmental factors and the lack of suitable systematic empirical studies, we will not phrase an explicit hypothesis relating environmental factors to project success.

In the next section we describe our research design and data acquisition followed by a section presenting our statistical findings on open design. Building on this background we will then evaluate the five hypothesis in the fifth section.

Approach and methodology of empirical research

In order to collect data concerning practical applications we launched a community–based directory of open design projects on 26 August 2008. Registration is for free and participants are encouraged to contribute by entering new projects as well as by maintaining all the information up–to–date.

The platform has been quickly embraced by the larger open source community. After one year, we count 66 registered members and observe fairly satisfactory numbers of visitors, exhibited in the left part of Figure 2. The chart shows the number of unique human visitors per month and visualizes a fluctuating, but strong increase of attention.

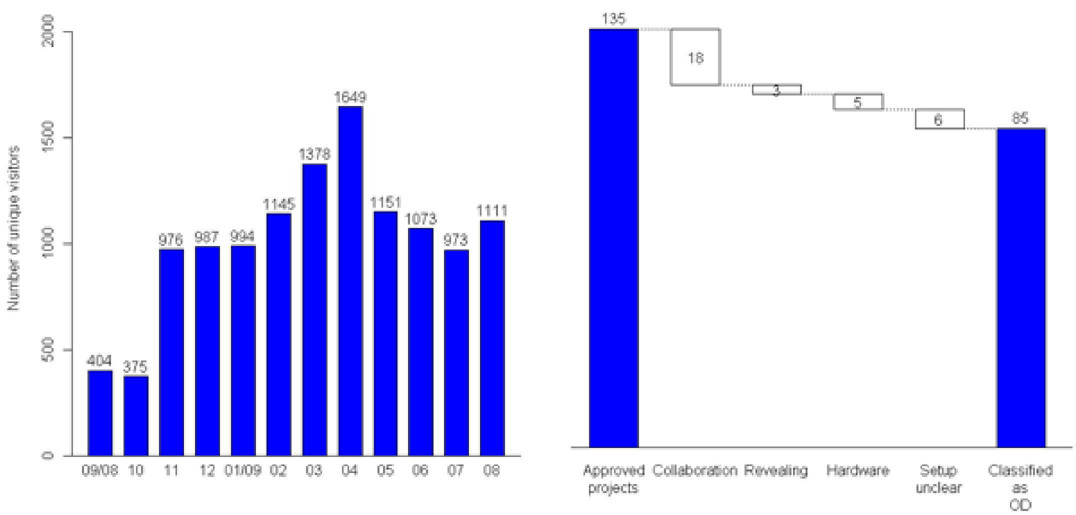

Figure 2: Upgrowth of unique human visitors from September, 2008 to February, 2009 (left) and break down of approved projects on reasons for exclusion and selected cases (right).

To our knowledge, our site (open–innovation–projects.org) contains the largest existing online directory collecting and providing information about open design projects. Since its inception, 135 project entries have been created, of which we need to exclude 18 due to complete inappropriateness. Accordingly we arrive at 117 relevant projects.

Every entry is carefully checked and only approved information is visible online and integrated into the database. The quality check not only eliminates spam entries; it primarily avoids that information is purely based on declarations of the project administrators rather than on objective measures. This is particularly important for attributes as complexity or innovativeness, where we take care to apply the same scale to all projects. Missing data is filled as far as the respective information on projects is available. In some cases project representatives have been contacted and asked to provide specific details.

In a second step, we analyzed each entry to check project conformity with the definition of open design. As shown in the right side of Figure 2, 85 projects have currently been identified as such, while 32 projects have been excluded due to the following reasons:

- In 18 approved projects we observe pure revealing of information without the intention for collective development required by the definition of open source innovation. Examples are communities of hobbyists exchanging their ideas and instructions on sewing patterns or IT hardware components;
- Three projects are abandoned, because they do not freely reveal relevant information. Those projects could be tagged 'Open Innovation' according to Chesbrough, *et al.* (2006). In these projects companies solicit ideas from the community, but do not share their knowledge for open co–development;
- Another five cases have been excluded due to our focus on physical goods. Those cases include projects as, for example OpenStreetMap and Open Source Cookbook, which should be considered open content rather than open design;
- Six entries could not yet be classified, because their approaches towards collaboration are not yet clear.

The data presented has been obtained as of 26 August 2009. For the purpose of statistical analysis we chose the software package 'R'. For detailed explanations of variables please refer to Appendix A.

Validity and limitations of the data base

Although we have thus established a reasonably large directory with 85 open design projects, 85 is a small number compared to about 150,000 OSS projects hosted at Sourceforge. Since there is no corresponding platform for open design, a comprehensive database of all existing projects is difficult to generate. Based on our research and expert interviews, we are confident to include the majority of open design projects, but we still have to be careful when generalizing results.

Concerning the actual data, it has to be noted that our data base is not fully filled and that some information is missing which could not be obtained from secondary sources. Our quality checks allow for adjustments based on an objective assessment, but critically depend on the availability of accurate secondary data.

Since our directory is fairly young, we only started to get input from the broader open source community. These caveats notwithstanding we already reveal a striking variety of projects and gain fairly deep knowledge about project and product details. In the following chapter we present a number of statistics demonstrating the diversity of projects and providing insights into their characteristics.

The variety of open design

In accordance with the selection criteria discussed in the previous section, we examine 85 open design projects along the framework presented in section 2, linking (1) actors, (2) artifacts, (3) governance structure, (4) development process, (5) innovative outcome, and (6) project environment.

Each of these encompasses multi–faceted issues reaching beyond the scope of this paper. In order to provide an exploratory overview, we will analyze all six parts, but focus on some aspects of particular relevance. We present univariate statistics using barcharts which show the number of projects per respective category. Due to data availability constraints not all data fields could be filled for some projects, which is why most plots do not sum to 85. Subsequently we focus on multivariate statistics in the last part of this section.

(1) Actors: Background and number of contributors

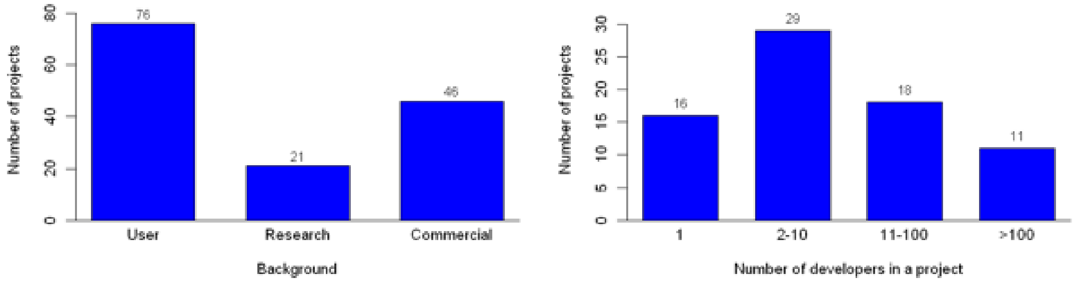

Figure 3: Background of contributing actors (left, multiple answers possible) and distribution of number of developers in projects (right).

Contributing actors stem from different backgrounds as shown on the left side of Figure 3. Different types of actors can contribute to the same project, hence the categories are not disjoint. The data contain 12 projects receiving substantial contributions from all three types, 41 projects from a combination of user and commercial actors, 17 projects from user and research and 14 projects from commercial and research.

Open design projects vary considerably in terms of community size and, more particularly, the number of developers. The right part of Figure 3 shows how the number of projects is distributed on the number of contributors. While obviously a number of project leaders did not manage to attract any further contributors, other projects have to deal with the coordination of hundreds of, in some cases even more than 1,000, active developers. As in similar analyses in the field of OSS, the chart suggests a left–skewed distribution.

(2) Object: Type of products and complexity

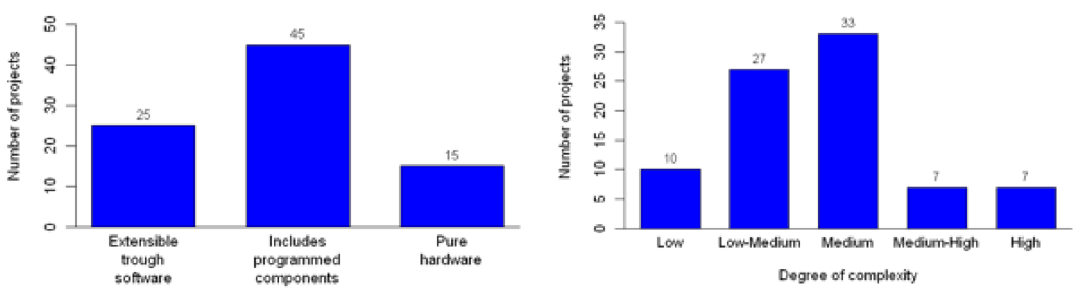

Figure 4: Importance of source code across projects and distribution of complexity of the final product.

In all considered cases, the artifact being developed is a tangible object, but information on the artifact is frequently digitalized for exchange during product development. Many projects incorporate written software code as a substantial part. We therefore categorize projects according to the type and amount of code that has to be developed (Figure 4, left).

The first category 'Extensible through software' includes all products whose functionality can be extended through software applications, *e.g.*, laptops, mobile phones, and programmable robots.

The second category 'Includes programmed components' contains products which require software to fulfill their intended functionality [4], but whose functionality cannot be extended through software applications, *e.g.*, printers, cars, and medical prosthetics. A laptop, for example, can gain entirely new functionalities if new software programs are installed, whereas a printer, for example, will only be able to print and its functionality cannot be extended through adding software applications.

'Pure hardware', the third category, includes all products which do not need a single line of code, *e.g.*, beverages and clothes.

With 25 projects in the first category, about one third of the examined projects bear particular resemblance to OSS projects: The product might supply, for example, a software development kit (SDK) allowing developers to create suitable applications. However we observe important differences to pure software development, as, for example, contributors need access to detailed hardware information in order to extend a products functionality.

More than half of the cases belong to the second category, where hardware development plays the major role and software development fades into the background, but remains important to control functionality. Both information on hardware, *e.g.*, in the form of descriptions, specifications, schematics, etc., and software code are exchanged.

In the third category the digitization of information happens, for instance, in terms of construction manuals, sewing instructions or recipes.

The right part of Figure 4 shows the distribution of different complexity levels ranging from as simple as beer and lights to as complex as cars and intricate machines, visualizing that all levels of complexity are being tackled by open design projects.

(3) Governance structure: Protection of intellectual property

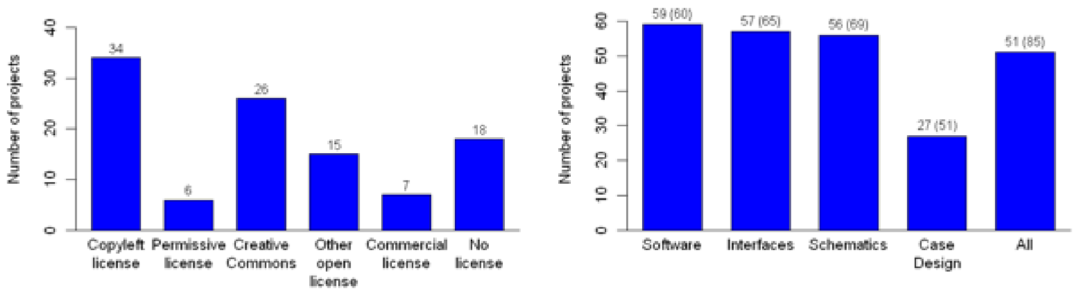

Figure 5: Figure 5: Type of selected license (left,multiple answers possible) and degree of openness (right).

As Figure 5 (left) illustrates many open design communities make use of an open license. The two major categories of free software licenses are copyleft and permissive or non–copyleft. While copyleft licenses such as the GNU General Public License (GPL) are highly restrictive and insist that modified versions of the program must be free software as well, permissive licenses such as the Berkeley Software Distribution (BSD) license are less restrictive and allow modifications to remain closed source. Beyond software, Creative Commons provides a menu of free licenses that copyright owners can use when releasing their work. These licenses delimit certain rights to the use of the work and differ in their restrictiveness, depending on the chosen type of license.

We observe that more than 50 percent of the projects make use of software licenses for software components. 30 percent use Creative Commons licenses for hardware parts. In 20 percent of the cases intellectual property is released without any license. In addition 25 cases (~ 30 percent) decided to protect their name by registering a trademark.

We further observe that many projects carefully select which knowledge to keep secret and which parts to reveal freely. The right chart of Figure 5 shows the number of projects revealing information across four categories — software, interfaces, schematics, and case design, and summarizes these categories in the last stack, which presents projects laying open all relevant information across all four categories.

The numbers in brackets indicate the total number of projects for which this category is relevant. By relevant we mean that the respective artifact includes parts of this category and development work on those parts has already started such that the question of revelation thus arises.

This analysis shows that it is common across all examined projects which include software development to open at least parts of their software. About 80 percent publish schematics or similar information and only half of the relevant projects decided to release their case design. Assuming that the revelation of knowledge is based on conscious decisions, one might conclude that projects typically derive more advantage from publishing software source code than from publishing other parts of their design.

(4) Development process: Responsibility for development and production processes

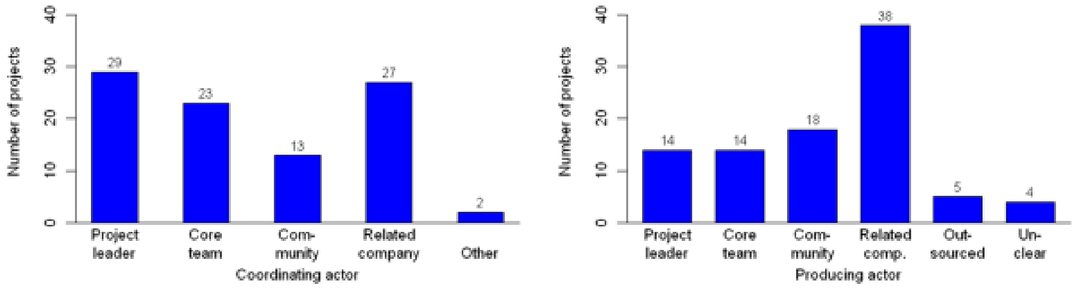

Figure 6: Distribution of actors promoting and coordinating the development (left) and of producing actors (right), multiple answers possible.

At this early stage it is hard to capture process evolution and efficiency on a quantitative basis. With Figure 6, illustrating which group of actors is mainly driving a project and which takes the role of the producer, we gain first insights into different configurations of development and production processes. Projects which have not yet started the production of prototypes or final products are tagged 'Unclear' in the right chart.

The chart visualizes that for a large proportion of examined projects the development is driven by a company (20–30 percent), and even more products are marketed and produced by a related company (~ 45 percent), even though the project might be community–driven. Correspondingly the plot shows that in 70–80 percent of the projects the product development is driven by private contributors, *i.e.*, by the project leader, the core team or even the larger community without a dedicated authority. In about half of the respective cases this group also acts as producer, the second half interacts with a company supporting production and marketing. Furthermore we observe five projects outsourcing the production of the entire product.

More details on the development process, particularly on the intensity of cooperation within projects, will be discussed in section 4 using multivariate statistics.

(5) Innovative outcome: Development stage, target group, and innovativeness

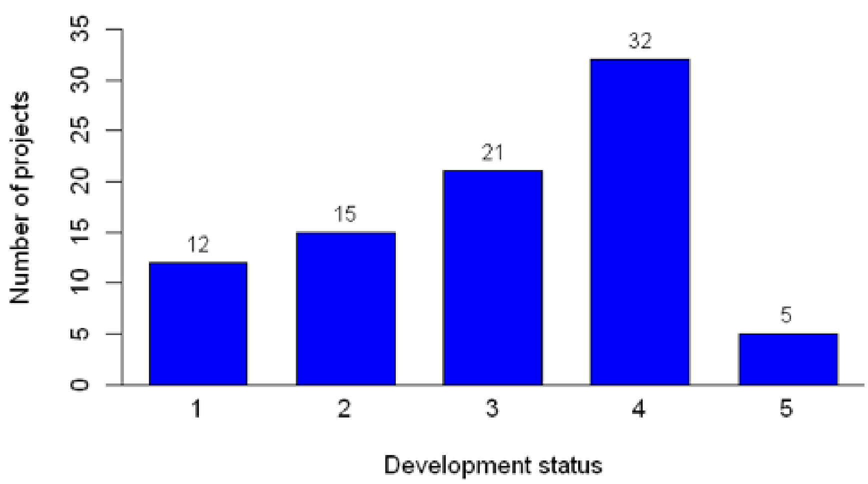

Figure 7: Distribution of stages of advancement in projects: 1 — Planning/Virtual development, 2 — Prototyping started, 3 — First working prototypes, 4 — Production stable, 5 — Mature.

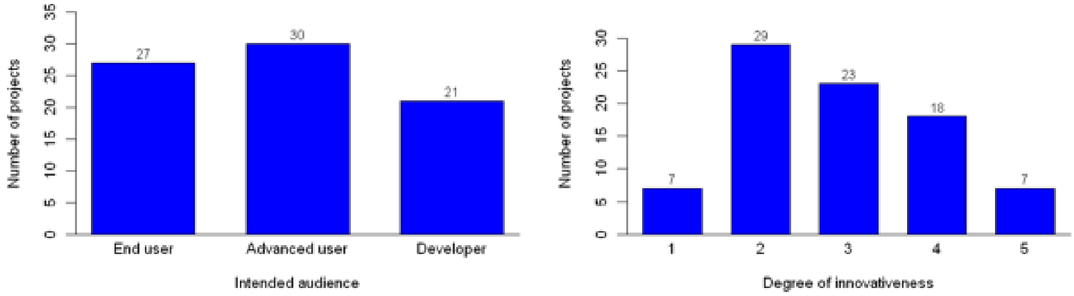

Figure 8: Distribution of intended audience (left) and degree of innovativeness: 1 — Imitative innovation, 2 — Incremental innovation, 3 — Discontinuous innovation, 4 — Really new innovation, 5 — Radical innovation (right).

Figure 7 shows that most projects have not entirely completed development, but about 50 percent have reached a stable production stage and are marketing their products. One could argue that the distribution is skewed due to the fact that our database is fairly new and we started by entering projects known to us or other experts we talked to. This approach naturally leads to larger and more advanced projects. However, one could also argue the other way around as new and small projects profit more from our directory and have accordingly a higher incentive to enter information. On balance we believe that the database is representative and comprehensive.

As development success is hard to evaluate across projects in different stages of advancement, the rest of this section remains limited to some preliminary findings on the intended audience and the degree of innovativeness (Figure 8). The distribution of projects across target customers is quite uniform, which leads to the assumption that open design products are generally suitable for end users, advanced users, and developers. For the categorization of innovativeness we follow Garcia and Calantone (2002) and evaluate the degree of innovativeness in five categories. Our cases reveal that open design is applied to the whole spectrum from the generation of incremental to radical innovations with a higher proportion striving for incremental or intermediate degrees of innovativeness.

(6) Environment: Industry and tool support

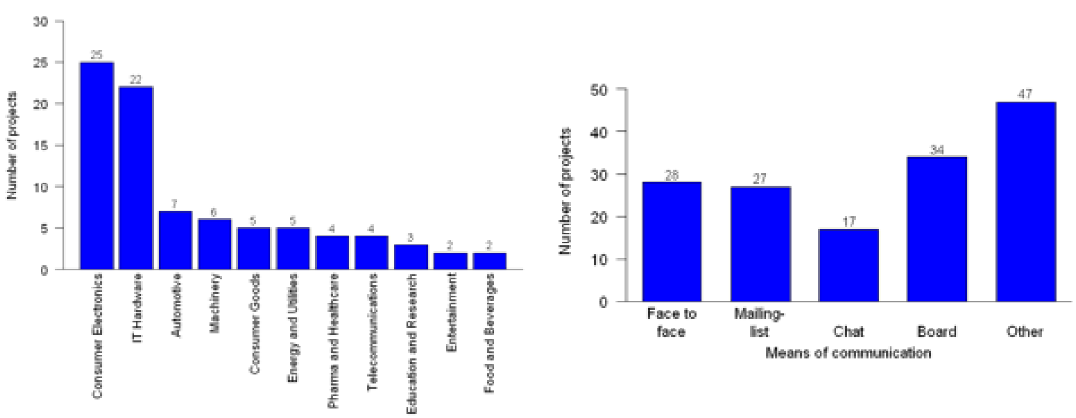

Figure 9: Distribution of industries (left) and means of communication (right, multiple answers possible).

The project environment spans a wide range of topics, from technologies and tools to the legal and social framing. The left side of Figure 9 illustrates the variety of industry backgrounds of our projects, visualizing that open design is already being applied in a number of different industries ranging from very traditional industries such as 'Food and Beverages' or 'Energy and Utilities' to industries such as 'Consumer Electronics' and 'Telecommunications'.

Another point worth investigating is the use of various tools for communication, development and archiving (Figure 9, right) allowing distributed participants to overcome constraints on communication and to access shared digital resources. Most common means of communication are mailing lists, chats and discussion boards, where most projects make use of more than one tool.

In the last stack 'Other' we summarize mostly newer communication technologies. It includes wikis and shared workspaces facilitating the cocreation of content across large, distributed sets of participants, blogs and podcasts offering individuals a way of sharing information with a broad set of other individuals, and social networks or hosting providers such as Sourceforge, offering contact management and access to hosting services.

Multivariate analysis

To gain first insights on relationships between variables we examine correlation coefficients and multivariate comparisons using relative measures as in Figure 10, where the diagrams are scaled to 100 percent to show trends in the data set. Correlations (ρ) are calculated as Pearson product–moment correlation coefficients giving a value between -1 and +1 inclusive. Significance levels of estimated correlations are obtained via analysis of p–values of two–sided tests for association between paired variables in order to confirm or reject the hypothesis that the underlying correlation is not equal to zero. In case of missing data, the respective pairs are excluded from the calculation.

The left chart of Figure 10 visualizes the positive correlation between the number of active developers and stages of advancement of $\rho = 0.4$ confirmed by a p–value below one percent. One could conclude that larger projects reach higher stages of advancement or, vice versa, that projects grow while maturing. The correlation is even more pronounced when contrasting the total community size, including passive consumers and lurkers, and the development status ($\rho = 0.6$ with p–value < 1 percent).

The right chart visualizes the positive correlation between developer activity, measured by the frequency of communication and distinguishing between low, medium and high, and stages of advancement of $\rho = 0.5$ with a p–value below one percent. High activity appears to have a positive impact on development status.

Not surprisingly we also find a positive correlation between the number of contributors and their activity ($\rho = 0.4$ with p–value < one percent). It seems reasonable that more developers generate more activity.

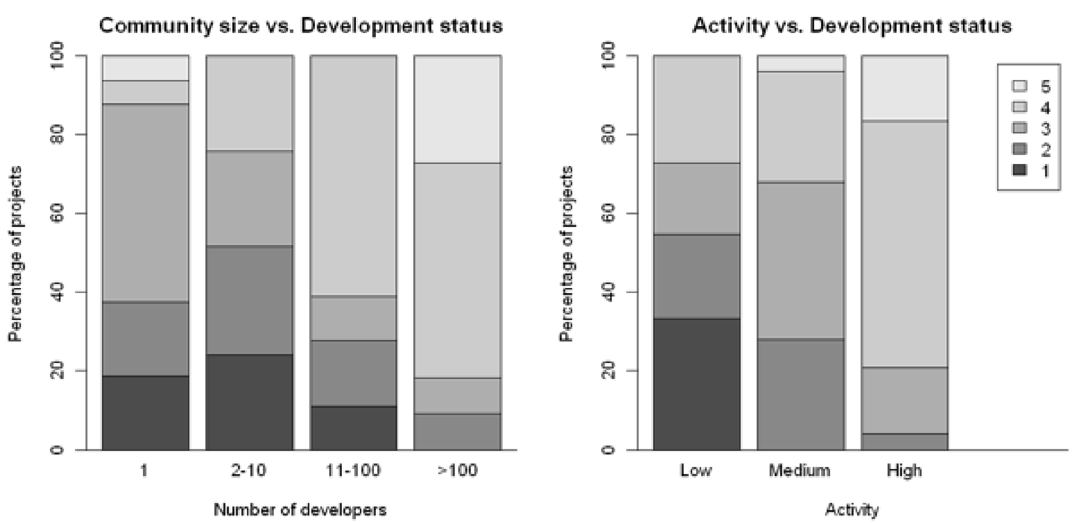

Figure 10: Comparison of developer community size (left) and activity (right) against development status; 1 — Planning/Virtual development, 2 — Prototyping started, 3 — First working prototypes, 4 — Production stable, 5 — Mature; in percent.

More details on correlations between selected attributes are summarized in Table 1. Exhibited are pairs of variables with absolute correlation values above 0.25 and high significance, *i.e.*, p–values below five percent, which point to relationships between different constituents of our underlying framework. Strong correlations between different variables of the same aspect, as it would be the case for open interfaces and open schematics, for example, shall not be the focus of this analysis. Due to space constraints in the table they are only partly exhibited.

Remarkable is the strong positive relationship between development status, the presence of commercial contributors and a registered trademark. Commercial actors seem to favor to protect their work by registering the projects name, which is less often the case for private or research actors. Furthermore commercial contributions seem to have a positive impact on stages of advancement, a correlation which has to be further examined as the relationship might also be due to companies joining projects in later stages or projects founding companies in order to market their products. The correlation between late stages of advancement and registered trademarks may be easily explained as it might make more sense to protect a project's name if success is augured.

We observe strong negative correlations between entirely open projects and the presence of commercial contributors as well as registered trademarks and between the size of the community and the absence of licenses as well as complete openness. Both the absence of licenses and complete openness might reflect a general absence of IP strategies which seems to reduce the community size and is rarely observed if commercial actors are involved.

The data show a positive correlation between the degrees of complexity and innovativeness. This relationship could arise from biased entries as both categories may be subject to biased perception of the person entering the data. However to avoid this type of bias we carefully checked every entry made by external contributors, and only approved entries are being considered in our analysis. Accordingly we arrive at the observation that projects developing highly complex products seem to or at least plan to achieve more innovative outcomes.

Table 1: Estimated correlations between selected variables.
Note: ** 1% and * 5% refer to the significance levels for the estimates.

	Commercial	Com. size	Complexity	No. licenses	Reg. trademark	Entirely open	Activity	Dev. status	Innovativeness
(1) Commercial	1								
Com. size	0.5**	1							
Complexity	0.1	0.1	1						
No. licenses	-0.1	-0.4**	0	1					
Reg. trademark	0.4**	0.5**	0.1	-0.3**	1				
Entirely open	-0.3**	-0.4**	0	0.2	-0.3**	1			
Activity	0.2	0.5**	-0.2	-0.2	0.3**	-0.2	1		
Dev. status	0.3**	0.6**	0	-0.2**	0.4**	-0.2	0.5**	1	
Innovativeness	0	-0.1	0.4**	0.2	-0.1	0.2*	0.1	-0.1	1

Furthermore we observe high positive correlations between the size of the developer community and commercial actors and registered trademarks, as well as between activity and registered trademarks, and a high negative correlation between community size and complete openness. These correlations are closely connected to the relations discussed earlier in this section and hint to high interrelations between the different variables. Closer investigation of dependencies among variables is required in order to arrive at secure evidence about actual relationships among the constituents of the open source innovation framework in Figure 1.

Discussion of results and comparison to OSS

Open source development seems feasible for tangible products. More and more physical products are being designed collaboratively via the Internet, but it is mostly early days to evaluate success. There are several promising precedents which have entered the market, though. In this section we discuss first implications of our findings for the hypotheses described earlier and point out ancors for further research.

(1) Actors: Quite a few open design projects manage to attract a sufficiently high number of active contributors, both from private and commercial backgrounds, to build a developer community and to achieve progress in terms of project advancement.

Compared to OSS repositories such as Sourceforge, our sample does not contain the large proportion of projects with just one developer, no discussion and no interest from the larger community. Healy and Schussman (2003), for example, arrive at the conclusion that for every successful OSS project there are thousands of unsuccessful ones. We are not claiming that this might be different for open design; however, we have so far not observed as many of those projects. This might partly have its seed in the definition of open source innovation, requiring the intention of collaborative development, and partly arise from the fact that the open design phenomenon and more particularly our directory is fairly new and accordingly the number of failed and inactive projects is low compared to large OSS repositories.

Our multivariate analysis confirms H1 for tangible products, showing a strong positive correlation between the size of the developer community and project advancement. As discussed in the previous section this might arise from different factors. On the one hand one might guess that projects tend to grow over time and that it could be easier for successful projects to attract considerable attention from the broader developer community; on the other hand a larger community might push ahead development. In the software realm, Krishnamurthy (2002) found no relationship between the release date and the number of developers associated. If this finding holds for open design, one may arrive at the conclusion that indeed a larger community positively influences project advancement.

H2 is likewise confirmed by our analysis revealing a positive correlation between commercial actors and project advancement. Taking both observations together, we find that projects with a large community, which includes commercial actors or is even organized by professionals, have a high likelihood of reaching advanced stages of development.

(2) Object: Although the comparison of object characteristics between open design and OSS is only meaningful to a certain extent, we want to highlight three particular aspects — the complexity of the object, its modularity and its digitization.

All levels of complexity can be observed across the examined artifacts and no strong evidence could be found pointing out that low– or high–complexity products are more suitable for open source development.

We further observe that complex objects frequently are modularized into manageable pieces and developed separately. This observation reveals similarities to OSS development, where this finding has been reported by Baldwin and Clark (2006).

Our third observation is that participants make a large effort to enable digital design and development as far as possible. In addition, the development of 3D printers, CNC cutters and similar tools for home use increasingly enables developers to produce their own designs independently of a central production. With the emergence of communities around the necessary equipment to share expenses and ease access, decentralized production becomes increasingly accessible. Thus a focal producer providing the products is no longer a necessity, and open development of physical products becomes yet more similar to OSS development. Further examination of this phenomenon is clearly required in order to assess its potential to reach a larger audience and estimate its impact on open source development beyond software.

(3) Governance structure: Open design projects generally tend to make use of an open license, but licensing is less straightforward than for OSS. H3, proposing that projects distributed under highly restrictive terms are less likely to reach an advanced stage of development, is not reflected in our data set.

We rather observe a positive correlation between trademark protection and late stages of advancement, and an interrelation between license–free release of information and small projects in early development stages. As discussed this might reflect the general existence or absence of IP strategies and their influence on project success. However, we could not determine a clear-cut relationship between sophisticated strategies towards revealing of certain components under certain rights and development status.

(4) Development process: Across our case database we observe different groups of actors being responsible for the creation of a product concept, the actual development work, and the final production, but find no formally distinguishable patterns.

We do find a strong correlation between the intensity of developer activity and development stage, confirming H4. As a result we conclude that both OSS and open design projects with higher activity tend to be in more advanced stages of development. However, in both fields further research is required in order to arrive at conclusions about the impact of process design on project success.

(5) Innovative outcome: Open design projects tackle both incremental improvements and radically new designs. For both extremes our data provide examples with fairly high development status.

We observe projects, which are in late stages of advancement, either addressing developers or advanced users or developing products suitable for end users. H5 proposing that applications for sophisticated users are more likely than others to reach advanced stages of development is not supported by our data.

Given that Comino, *et al.* (2007) derived their hypothesis from findings on the motivation of participants, our observation could hint to differences in the reasons for contributing between open source software and tangible goods. Clearly further investigation is required prior to deriving conclusions on this topic.

(6) Environment: Our examples stem from a variety of different industries with a large subset in consumer electronics and IT hardware. The development of these products does not only typically involve a large amount of software development, but many of these products are also shapeable through software. This characteristic makes them very attractive for open source software enthusiasts. For instance, by changing a mobile phone's software users can add new functionalities and customize their device to a high degree; and through access to hardware interfaces developers can modify the purpose of a chip. Both examples illustrate potential reasons for the desire to gain access to relevant information. This may explain the rise of open development activity in those industries.

A precondition for the feasibility of the OSS phenomenon is the existence of strong supporting tools, in particular the Internet, that are easily accessible to the developer community. For open design, especially in the technical domain, new suitable tools seem to be of particular importance to enable digital development of tangible artifacts. We encountered, for example, free or cheap design software, platforms for the exchange of designs, and open source equipment for prototype production. In other cases we also observed how the absence of required tools decelerates the entire development work.

Summary and conclusions

In this paper, we investigated a comprehensive data base of open design projects, with the aim of exploring the landscape of open source development in the world of atoms, analyzing project characteristics, structures, and success, and investigating similarities and dissimilarities to open source software development. Cases have been identified according to the definitions of open source innovation and open design and carefully maintained during data collection. Along the open source innovation framework we presented a number of statistics describing common patterns among examples. A principal finding was that open design is already being implemented in a substantial variety of projects.

Open source development of tangible goods is not a new, but a rapidly evolving field, and more and more physical products are being designed collaboratively via the Internet. Contributors from private and commercial backgrounds form communities with sizes varying from one to several hundred developers and tackle the development of products across all degrees of complexity and innovativeness. The considered projects stem from various industries and show diverse contextual backgrounds. Their current development stages range from the evolvement of first rough ideas to mature and successfully marketed products. The largest proportion of projects already has fully functional products permanently available on the market, but is still working on further development.

Hypotheses derived from the literature on open source software were tested in the context of open design using our data set. We found strong relationships between the stage of advancement of the development and the size of the developer community, the presence of commercial contributors, and the intensity of cooperation, respectively.

We indicated that, in open design communities, tangible objects can be developed in very similar fashion to software; one could even say that people treat a design as source code to a physical object and change the object via changing the source. This suggests the transferability of the 'open source model' to different industries beyond software. The success of OSS warrants a closer investigation of its potential to generate innovative and commercially viable products in other domains. With our contribution we hope to highlight the demand and smooth the way for further research on this rising phenomenon.

About the authors

Kerstin Balka is research fellow at Hamburg University of Technology (TUHH) at the Institute of Technology and Innovation Management. Her research interests focus on open source innovation and in particular on empirical studies of open design projects.
E–mail: kerstin [dot] balka [at] tu–harburg [dot] de.

Christina Raasch is a post–doc researcher and lecturer at Hamburg University of Technology (TUHH) at the Institute of Technology and Innovation Management. She is head of the Open Source Innovation Research Unit. Her current research focuses on open and collaborative models of new product development. She has published her work in several leading peer–reviewed journals as well as three books.
E–mail: raasch [at] tu–harburg [dot] de.

Cornelius Herstatt is Managing Director and full professor at the Institute for Technology and Innovation Management (TIM) at the Hamburg University of Technology (TUHH). He has published various books and more than 140 articles, focusing on innovation management. His main research areas are the management of innovation projects and the involvement of lead users and user communities in the new product development process as well as innovation in the context of demographic change.
E–mail: c [dot] herstatt [at] tuhh [dot] de.

Acknowledgements

Our sincere thanks are due to our community members for their time and support of our project. Furthermore we gratefully acknowledge the generous support of our research by the German Federal Ministry for Education and Research (BMBF) (project code 16|1573).

Notes

1. Dahlander and Magnusson, 2008, p. 646.

2. With regard to content we keep the six constituents, however we adapt the graphical representation to visualize the relations among the constituents.

3. Healy and Schussman, 2003, p. 18.

4. covering microprocessors, digital signal processors (DSPs), and programmable logical devices, like field–programmable gate arrays (FPGAs), requiring written source code in a programming or description language to fulfill their intended functionality.

References

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

A. Bonaccorsi and C. Rossi, 2003. *Licensing schemes in the production and distribution of open source software: An empirical investigation*. SSRN eLibrary, at http://papers.ssrn.com/, accessed 1 November 2009.

H. Chesbrough, W. Vanhaverbeeke, and J. West (editors), 2006. *Open innovation: Researching a new paradigm*. Oxford: Oxford University Press.

S. Comino, F.M. Manenti, and M.L. Parisi, 2007. "From planning to mature: On the success of open source projects," *Research Policy*, volume 36, number 10, pp. 1575–1586.

K. Crowston and B. Scozzi, 2002. "Open source software projects as virtual organisations: compentency rallying for software development," *IEE Proceedings — Software*, volume 149, number 1, pp. 3–17.

L. Dahlander and M. Magnusson, 2008. "How do firms make use of open source communities," *Long Range Planning*, volume 41, pp. 629–649.

B. Demil and X. Lecocq, 2005. "Neither market nor hierarchy or network: The emerging bazaar governance," *Organization Studies*, volume 27, number 10, pp. 1447–1466.

R. Garcia and R. Calantone, 2002. "A critical look at technological innovation typology and innovativeness terminology: A literature review," *Journal of Product Innovation Management*, volume 19, pp. 110–132.

K. Healy and A. Schussman, 2003. "The ecology of open–source software development," Department of Sociology. University of Arizona, at http://www.kieranhealy.org/files/drafts/oss-activity.pdf, accessed 1 November 2009.

E. von Hippel and G. Krogh, 2003. "Open source software and the 'private–collective' innovation model: Issues for organization science," *Organization Science*, volume 14, number 2, pp. 208–223.

J. Hope, 2007. Pharmaforschung mit open source-methoden. In: B. Lutterbeck, M. Bärwolff, and R.A. Gehring (editors). *Open–source–jahrbuch 2007: Zwischen freier software und gesellschaftsmodell*. Berlin: Lehmanns Media, pp. 73–85.

S. Krishnamurthy, 2002. "Cave or community? An empirical examination of 100 mature open source projects," *First Monday*, volume 7, number 6, at http://firstmonday.org/htbin/cgiwrap/bin/ojs/index.php/fm/article/view/960/881, accessed 1 November 2009.

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

J. Lerner and J. Tirole, 2004. "The economics of technology sharing: Open source and beyond," *Harvard NOM Working Paper*, number 04–35., at http://papers.ssrn.com/, accessed 1 November 2009.

G. Mueller–Seitz and G. Reger, 2008. "Open beyond the source code? An explorative examination of the development of an open source car," *Proceedings of the EIASM IPDM Conference*.

A. Nuvolari and F. Rullani, 2007. "Curious exceptions? Open source software and 'open' technology," In K. St. Amant and B. Still (editors). *Handbook of research on open source software: Technological, economic, and social perspectives*. Hershey, Pa.: Information Science Reference, pp. 227–236.

M. Osterloh and S. Rota, 2007. "Open source software development: Just another case of collective invention?" *Research Policy*, volume 36, pp. 157–171.

G. Parker and M.W. van Alstyne, 2005. "Two—sided network effects: A theory of information product design," *Management Science*, volume 51, number 10, pp. 1,494–1,504.

C. Raasch, C. Herstatt, and K. Balka, 2009a. "On the open design of tangible goods," *R&D Management*, volume 39, number 4, pp. 382–393.

C. Raasch, C. Herstatt, K. Balka, and N. Abdelkafi, 2009b. "The open source model - beyond software," *EURAM conference paper*.

E. Raymond, 1999a. "Afterword: Beyond software?" at http:// www.catb.org/~esr/writings/cathedral-bazaar/afterword/ (version 3.0).

E. Raymond, 1999b. "The cathedral and the bazaar," *Knowledge, Technology, and Policy*, volume 12, number 3, pp. 23–49.

M.A. Rossi, 2004. "Decoding the f/oss puzzle: a survey of theoretical and empirical contributions," University of Siena, Department of Economics Working Paper, number 424.

C. Royal and D. Kapila, 2009. "What's on *Wikipedia*, and what's not …? Assessing completeness of information," *Social Science Computer Review*, volume 27, number 1, pp. 138–148.

S.K. Shah, 2005. "Open beyond software," In: D. Cooper, C. DiBona, and M. Stone (editors). *Open sources 2*. Sebastopol, Calif.: O'Reilly Media, pp. 339–360.

C. Shirky, 2007. "Generalizing peer production into the physical world," at http://finance.groups.yahoo.com/group/decentralization/message/6967, accessed 2 November 2009.

Z. Smith, 2008. "Objects as software: The coming revolution," *25th Chaos Communication Congress*, at http://events.ccc.de/congress/2008/Fahrplan/events/2781.en.html, accessed 2 November 2009.

C. Thompson, 2008. "Build it. Share it. Profit. Can open source hardware work?" *Wired*, volume 16, number 11, at http://www.wired.com/print/techbiz/startups/magazine/16-11/ff_openmanufacturing, accessed 2 November 2009.

G. von Krogh and E. von Hippel, 2006. "The promise of research on open source software," *Management Science*, volume 52, number 7, pp. 975–983.

D. Weiss, 2005. "A large crawl and quantitative analysis of open source projects hosted on SourceForge," Institute of Computing Science, Poznań University of Technology, Poland, Technical Report, number RA–001/05, at http://www.cs.put.poznan.pl/dweiss/site/publications/download/weiss-2005-large-crawl-of-sourceforge.pdf, accessed 2 November 2009.

Appendix A: Variable explanations

(1) Contributing actors

- User contribution — Specifies whether private persons or users are actively involved in the development
- Commercial contribution — Specifies whether commercial companies are actively involved
- Research contribution — Specifies whether research institutions are actively involved

(1) Developers

The approximate number of active developers contributing to this project.

(2) Product complexity

The estimated degree of complexity for the developed product ranging from low complexity, *e.g.*, a simple wooden chair, to high complexity, as for example an aircraft or a nuclear power plant.

(3) License

Indicates if the project is using an open license and specifies the type, including a mark whether they have a registered trademark.

(3) Degree of openness

- Software — Software and other non–physical, content parts are open source.
- Interfaces — Hardware specifications and interfaces are layed open.
- Schematics — Mechanical parts, descriptions, PCBs, etc. are freely available.
- Case design — If applicable the case design is available, *e.g.*, as CAD for download.
- Entirely open — The project is revealing all available information.

(4) Development driver

Specifies the main drivers of the development, *i.e.*, the group(s) of people pushing forward the project. Related company or association refers to a company closely related to the project, for example the investing company.

(4) Production

Specifies the group(s) of people responsible for producing the product. Related company or association refers to a company closely related to the project or a company with an exclusive production mandate. 'Outsourced' is checked whenever an external party is paid for taking over the production.

(4) Activity

The activity level in the community or developer group from low (up to one interaction per month on average) to high (daily interaction).

(5) Development status

1. Planning/virtual development — Ideas and digital development evolving
2. Prototyping started — First physical prototypes assembled, testing phase
3. First working prototypes — Working prototypes available, release to community, further development needed
4. Production stable — Fully functional product permanently available on market, further development possible
5. Mature — Final development stage reached, no further development necessary

(5) Intended audience

- End user — Everybody from school kids to your grandmother
- Advanced end user — Product will target end users, but usage may require specific knowledge
- Developer — No intention to reach end users, high specific knowledge necessary

(5) Product innovativeness

- Radical innovation — a new technology that results in a new market infrastructure, *e.g.*, an innovation which does not address a recognized demand but instead creates a demand previously unrecognized by the consumer
- Really new innovation — a really new product results in a market discontinuity or a technological discontinuity but will not incorporate both, *e.g.*, new product lines, product line extensions with new technology, or new markets with existing technology
- Discontinuous innovations — new technologies that don't lead to discontinuity in existing markets
- Incremental innovations — products that provide new features, benefits, or improvements to the existing technology in the existing market
- Imitative innovations — imitative products are frequently new to the firm, but not new to the market

(6) Means of communication

- Face–to–face — Participants frequently interact in person
- Mailing lists — At least one mailing list is used frequently
- Chat — The community has at least one active chat
- Board — A board/discussion forum is used
- Other — Other communication channels as wikis, blogs, etc. have been established

---

Editorial history

Paper received 10 September 2009; accepted 9 October 2009.

Open source enters the world of atoms: A statistical analysis of open design
by Kerstin Balka, Christina Raasch, and Cornelius Herstatt.

First Monday, Volume 14, Number 11 - 2 November 2009
http://www.uic.edu/htbin/cgiwrap/bin/ojs/index.php/fm/article/viewArticle/2670/2366