ISSUES IN OPEN HARDWARE

What is the "Source" of Open Source Hardware?

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What "open source" means once applied to tangible products has been so far mostly addressed through the light of licensing. While this approach is suitable for software, it appears to be over-simplistic for complex hardware products. Whether such a product can be labelled as open source is not only a question of licence but a question of documentation, i.e. what is the information that sufficiently describes it? Or in other words, what is the "source" of open source hardware? To date there is no simple answer to this question, leaving large room for interpretation in the usage of the term. Based on analysis of public documentation of 132 products, this paper provides an overview of how practitioners tend to interpret the concept of open source hardware. It specifically focuses on the recent evolution of the open source movement outside the domain of electronics and DIY to that of non-electronic and complex open source hardware products. The empirical results strongly indicate the existence of two main usages of open source principles in the context of tangible products: publication of product-related documentation as a means to support community-based product development and to disseminate privately developed innovations. It also underlines the high variety of interpretations and even misuses of the concept of open source hardware. This reveals in turn that this concept may not even be clear to practitioners and calls for more narrowed down definitions of what has to be shared for a product to be called open source. This article contributes towards this effort through the definition of an open source hardware lifecycle summarizing the observed approaches to open source hardware.

1 Introduction

In present times, we are witnessing increasing numbers of initiatives transferring product development and production from the private sector to the public. Enabled by the growing accessibility of affordable manufacturing technology, this is manifested in the expansion of the so-called "maker culture" which takes action to install participative production as an alternative to industrial production (Hatch 2013; Voigt, Montero, and Menichinelli 2016). The emergence of this culture is interwoven with the phenomenon of open source hardware (OSH), which transfers open source principles (as defined by Open Source Initiative 2007) from their origins in software development to the world of physical objects (Balka 2011: 4). While these new practices are raising significant attention, they are still in their infancy and struggle to reveal their full economic,

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social and environmental potential. One of the challenges they face is that sharing knowledge about atoms is not as frictionless as sharing bits.

Both practitioners and the scientific community generally acknowledge that online sharing of a piece of hardware is more difficult than the sharing of a piece of software (for example see discussion of this point in Raasch and Herstatt 2011). Software is digital by nature; it is made of series of characters—a format that can be shared and displayed online without specific tools, with a text editor being enough. Hardware may need to be described through more complex constructs like 2D or 3D schematics, which may require more specific software to be edited and displayed. Based on the evaluation of a pool of 20 OSH projects whose products embedded both software and hardware components, Balka, Raasch, and Herstatt (2014) highlighted that hardware components were generally less documented than the software components. This result raises questions in terms of practice. When a piece of hardware is poorly documented, is it still open source? What does "less documented" mean? What are the minimal requirements for labelling a hardware product as open source?

In the absence of clear guidance on this issue, it is not easy to draw a line between which piece of hardware is open source and which is not, even when licensing terms

may be clear. Unlike in software, attributing appropriate licences[1] is not sufficient to call hardware open source. Given OSH is a sociotechnical phenomenon, the answer primarily depends on how the product documentation enables co-development and replication. This article seeks to provide guidance on which information sufficiently describes OSH. In other words, *what is the source of OSH?*

The objective of this article is to provide an overview of how current projects tend to interpret and make use of the concept of OSH. Its ultimate goal is to provide a deeper description of what OSH means based on the observation of actual practices. This is performed through the analysis of the "source", i.e. the published documentation, of 132 OSH products with the help of categorical criteria addressing the question *"how open are OSH products?"* It specifically focuses on the recent evolution of open source movement outside the domain of electronics and DIY to those of non-electronic and complex OSH products.

The remainder of the paper is structured as follows: In the next section the general context of emergence of OSH as an alternative product development pattern based on free distribution of information is depicted and characterized. In section 3 definitions from practice communities and scholars are analysed and combined in order to provide a consolidated overview of the concept of OSH. In section 4 the methodological approach for the acquisition of empirical data allowing the analysis of current practices of OSH documentation is introduced. The results produced by the application of this method are then described and interpreted in section 5. Finally, Section 6 summarizes the findings into an original framework termed *OSH lifecycle* summarizing observed approaches to OSH.

2 The Context of Open Source Hardware

OSH is a relatively young phenomenon with projects emerging in the past decade (Balka 2016), although it has several prominent examples already. Pioneering projects such as RepRap, Open Source Ecology, or Local Motors have certainly set a precedence to lift the air of mystery and aloofness of engineering ingenuity closely guarded for means of commercial appropriation. As to whether these are heralds of what Moritz et al. (2015) depict as disruptive changes on the upstream end of value chains toward value-co-creation, only time will tell. Clearly, this alternative course of action could take an active part in shaping the technological future. Indeed, there are already promising examples of successful businesses based on OSH for which the scientific community identified corresponding value creation models (Pearce 2017; Li et al. 2017). These examples, together with the empirical evidence provided by free and open source software, allow for a foreseeing of a flourishing future for OSH (*ibid.*).

Like free and open source software, OSH is an IT-enabled internet phenomenon. Fjeldsted et al. (2012) as well as Bonvoisin and Boujut (2015) point out the integral part IT platforms play in fostering product-related data sharing, community-based product development as well as the emergence of OSH-based business models. However, Raasch and Herstatt (2011) draw a contrast: compared with OSS development, the aspect of physical object design in OSH has strong impacts on required skills, tools, and infrastructure. This aspect is even increasingly salient as the focus of OSH progressively expands towards many other forms of hardware than electronic hardware, like mechanical, construction, medical, optical, agricultural or textile hardware. From a design-point-of-view, the degrees of freedom in the problem-solution space introduced by their mechanical portion rise significantly. Howard et al. (2012) and Raasch, Herstatt, and Balka (2009) also illustrate how OSH is looking at the full spectrum of product complexity and different manufacturing strategies, from DIY to industrial production.

The capacity of communities outside the closed and hierarchical environment of R&D departments to develop complex and high quality products remains a challenge—the largest majority of OSH products available to date being gadgets for hobbyists (Hansen and Howard 2013). As processes transform inputs into outputs, their structure is generally related to the product and project scope. OSH can be described as individual or participatory realisation of a shared product design. Therefore, 3D printing designs shared by individuals on e.g. Thingiverse™,[2] may classify as OSH, just as large community-efforts like in the E-Nable project.[3] This makes a big difference to the type of effort being structured for the realisation of an open source product. Hence, depending on the product scope and also the originator/s' intent to foster co-design, levels of interaction maturity differ starkly in OSH. A useful macro-level classification is offered by Camarinha-Matos et al. (2009) from networks to coordination to cooperation to collaboration.

The conceptual space that supports collective spirit and collaborative problem solving is described by Maher, Paulini, and Murty (2011). It is based on the three aspects of shared representation, motivation and communication. They enable problem solving in collective design projects within a continuum from collected (individual) to collective intelligence. The latter is demarcated by collaborative generation of solutions as well as synthesis of individual solutions. From their study of collective design activities Paulini, Murty, and Maher (2011) conclude that—within the frame of what they call an inclusive nature of participatory design—individuals proactively self-organise and choose their own roles as well as period of involvement. The maturity of this participatory nature may in fact be the primary determinant of collective design projects.

Social dynamics in crowds are context-dependent however. In the OSH context, from all of the above, communities can be viewed as socially formed groups of heterogeneous actors who co-create OSH products. Depending on the participatory roles of actors, they may engage as followers, replicators, developers, or community managers. In the frame of open innovation, West and Lakhani (2008) describe them as actor volunteers lacking of organisational affiliation. Due to partial influence of market-based factors, this role may somewhat reflect the notion of people giving away their time and effort without any monetary compensation. In addition, actors may as well include individuals, firms, as well as any other types of organizations (von Hippel 2005: 4, 165).

Aksulu and Wade (2010) give an insight in how pure open source systems set a community-based context of personal development, process learning, as well as effective technology outputs. In contrast, within the purely proprietary context, purpose is realized by the efficient generation of technology outputs within organisations with clear boundaries.

What exactly makes open source processes effective seems to be rooted in the task environment. According to Lee and Cole (2003), the trade-off between exploration and exploitation is made through a two-tier task structure of generated variations within the periphery and selection and retention at the core. In their case study of the Linux kernel development project, they observe community-based knowledge creation in the form of an evolutionary learning process based on a culture of critical evaluations and peer learning. Moreover, Howison and Crowston (2014) describe collaborative development of OSS as an evolutionary process of incremental and independent tasks, by which a layer structure emerges task-by-task. They argue that added layers change the context over time and significantly reduce complexity of tasks. By gradually laying the foundation, previously unattainable tasks eventually may suddenly become easily achievable by individual developers, or simple workarounds may become obvious. This is in line with Maher's concept of co-evolution of the problem and solution spaces (1995), which describes how these dimensions influence each other during the design process. Collaborative evolutionary design on the activity level is key in explaining how solutions are generated effectively in open source systems[4] and needs to be further researched.

3 Definitions of Openness from Practice and Research

This section reviews existing definitions from practice and identifies resulting implications in terms of published product-related documentation. These definitions are then matched with existing contributions from research in order to provide a comprehensive framework defining OSH. Results of empirical studies which challenge these definitions and show a more heterogeneous landscape of OSH are then presented and lead to the identification of two research questions addressed in this article.

3.1 Definitions from practice communities
The Open Source Hardware Statement of Principles 1.0 states that: "open source hardware is hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design" (Open Source Hardware Association 2016). It is based on the assumption that publishing a "design" (alternatively termed "documentation") realizes the four freedoms of the open source concept which are reinterpreted in the context of tangible products as the freedom to study, modify, make and distribute.[5]

This definition is an adaptation of the original Open Source Definition by the Open Source Initiative (2007) to the realms of tangible products. Coined in the context of free and open source software, it specifies requirements on two interwoven objects: the "software", alternatively called the "product", and the "source code". It is implicitly accepted that the object called "source code" allows defining the object called "product" unambiguously in its depth and its entirety. While this implicit prerequisite is automatically fulfilled in the case of software—as a software product is the translation of a text written in programming language into a machine language by a deterministic algorithm—it is not the case of tangible products: what information has to be shared in order to allow any interested person to study, modify, make and distribute a piece of hardware is not a simple question.

A closer look at the definitions of widely recognized OSH licences and current practices of OSH seeks to give some hints and shows that the four freedoms of open source tend to be supported by different document types or properties (Bonvoisin and Schmidt 2017a):

- Freedom to *study* (i.e. the right to access sufficient information to understand how the piece of hardware—referred herein as the product—works and to retrace the underlying design rationale as defined by Wang, Johnson, and Bracewell 2012) can be supported by the publication of schematics, 2D or 3D CAD files.
- Freedom to *modify* (i.e. the right to edit the product definition documents and to tweak or develop the product further for any purpose) can be supported by the publication of all documents in their original editable format.
- Freedom to *make* (i.e. the right to use the product definition documents in order to make—in other words to produce, to manufacture—the piece of hardware) can be supported by the publication of bill of materials and assembly instructions.
- Freedom to *distribute* (i.e. the right to give or sell the product definition documents as well as the physical products fabricated with the help of these documents) is allowed by the publication of all documents under a licence which grants free redistribution including for commercial purposes.

3.2 Definitions from scholarly research
Scholarly definitions—mostly stemming from innovation management research—deliver categories which are consistent with the Open Source Hardware Statement of Principles 1.0 without, however, giving further details on the nature of the documentation to be published.

Freedoms to study, to edit and to make are consistent with the three factors of openness defined by Balka, Raasch, and Herstatt (2014). They respectively term these factors *transparency*, *accessibility* and *replicability*. Transparency refers to the possibility for any interested person to access sufficient information to understand the product in detail without restriction (equals *the freedom to study*). Accessibility refers to the possibility for any interested person to edit design information and therefore to further develop the product (equals *the freedom to modify*). Replicability refers to the possibility for any interested person to physically produce the

product (equals *the freedom to make*). These three factors of openness are introduced as preconditions for three complementary behaviours on the part of the community surrounding the product: Transparency enables observation (and eventually feedback), accessibility enables further development (and eventually co-development) and replicability enables prototyping and production (and eventually co-production). What is missing in this contribution is the fourth factor of openness termed henceforth *commercial usability*, which addresses the above listed *freedom to distribute*.

The four freedoms and corresponding factors of openness cover both "distinct and competing meanings" of openness identified by von Hippel (2010): the permeability of the innovation process to the participation of external people and the public sharing of documentation. Transparency, replicability and commercial usability are about sharing documentation publicly. Accessibility is about enabling the participation of external people in the design process. Aitamurto, Holland, and Hussain (2015) term two meanings of openness: *process openness* (whether the innovation process is open or closed) and *product openness* (whether the innovation outcome is open or closed). Huizingh (2011) defines open source innovation as a result of both process and product openness. Raasch, Herstatt, and Balka (2009) particularly deliver the following definition: "open source innovation is characterised 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 nonmarket exploitation".

The coherent picture of OSH drawn by those definitions from practice and scholarly research is displayed in **Figure 1**. OSH builds upon product and process openness. Product openness results from the factors transparency, replicability and commercial usability, which respectively address the freedoms to study, make and distribute. Process openness results from the sole factor accessibility, which addresses the freedom to edit.

3.3 Theory-practice-gap

The few existing empirical studies of OSH deliver a picture from practice observations that is less strict than the ambitious theoretical approach summarized by **Figure 1**—beyond the misuses which can be expected with the upcoming of a new concept.

Balka, Raasch, and Herstatt (2014) showed that factors of openness may be valued differently by development community members in the fields of consumer electronics and IT hardware. In the communities they analysed accessibility of software tended to play the largest role in the involvement of members, transparency and replicability of software was of secondary role and the openness of the related hardware played no role. They also highlighted that, as a result of the low importance given to hardware in those communities, hardware components were generally "less documented" than the software components. This raises the following research question:

> *RQ1 – To what extent are the four aspects of openness reflected by practitioners in the publication of product-related documentation? Do practitioners tend to employ the whole set of these factors, or do they tend to employ only subsets of these factors?*

Based on interviews with originators of OSH products, Bonvoisin et al. (2017) defined the contours of two archetypes of projects developing OSH they termed *development communities* and *isolated innovators*. Development communities are characterized by high process openness, adopt systematic and early release policies and gather contributions from a larger and permeable group of people. On the contrary, isolated innovators are characterized by a low process openness. They do not gather contributions from the outside, rather they release complete product documentations after product versions are fully developed. While the former are interested in integrating people from the outside during the product development
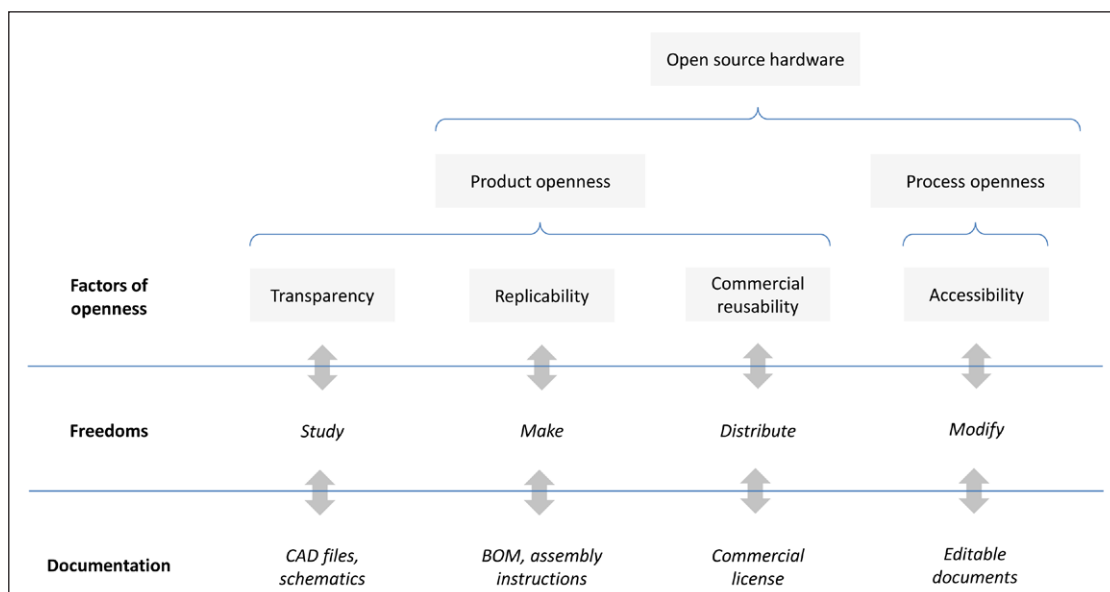

Figure 1: Forms of openness involved in open source hardware.

process, the latter are more interested in broadcasting their innovation, i.e. enabling other people to produce it. This contradicts the statement made by Gacek and Arief (2004) that "the term open source has been widely used to describe a software development process". Findings reported by Bonvoisin et al. (2017) suggest on the contrary that motivations for publishing documentation may depend on the phase of the product lifecycle in which the community is supposed to play a role and raise the following second research question:

> RQ2 – *If factors of openness are understood by practitioners as optional, can we find typical patterns in the way practitioners decide to comply with specific factors of openness? Are these aspects related to specific product lifecycle phases?*

4 Research Approach and Methodology

In order to address the research questions defined above, an empirical approach based on the systematic analysis of a representative group of OSH products as well as their published documentation has been adopted. This approach is similar to those adopted by Balka, Raasch, and Herstatt (2009, 2014), however, avoiding two pitfalls limiting the validity of the produced results. The first is the use of unclear categories such as the size of the development community. As shown in Bonvoisin et al. (2017), belonging to a development community is a fickle concept which may be based on different types of activities (from pressing the button "I like" to bringing significant contribution to the product design), which are highly flexible over time and therefore difficult to measure objectively.[6] The second is the use of subjective evaluation of the openness factors with the help of Likert scales. In contrast to the approaches of Balka, Raasch, and Herstatt (ibid.), the research reported here strives at a systematic analysis of published documentation with the help of measurable indicators, from the part of an impartial observer.

In the following subsections, the approach adopted for the acquisition and the analysis of empirical data is presented. The first subsection introduces methodological choice made in focusing on non-electronic complex hardware products. The second subsection describes the method applied for the establishment of a representative pool of those products. The third subsection defines a set of criteria used to characterize products and their related documentation. The fourth subsection defines criteria for the assessment of openness factors based on the acquired data. The last subsection introduces a clustering method used for identifying typical patterns in the publication of OSH documentation.

4.1 Focus: complex non-electronic hardware products

While the transfer of open source principles from software to hardware historically and logically started with electronic hardware (Gibb 2014), other technologies are increasingly impacted by the phenomenon. The extension of open source practices to non-electronic hardware such as mechanical products is of particular interest in terms of

documentation. Electronic hardware is a very standardized field where components are purchased off the shelf. But this is not the case for mechanical hardware where non-standardized free form components play a large role.

Also, particularly interesting is the consideration of complex products. Product complexity is defined by Jacobs (2007) as "a design state resulting from the multiplicity of, and relatedness among, product architectural elements". This characteristic influences the level of professionalization required in the development and production of a given product. It also determines whether production can take place in either DIY or industrial production settings. Noteworthy is that, while DIY and OSH are two interwoven phenomena, not every OSH product is meant to be produced in a DIY production setting (Bonvoisin, Galla, and Prendeville 2017). Product complexity also relates to design effort in terms of resources consumed and process duration (Rodriguez-Toro, Jared, and Swift 2004). Highly complex products tend to require inputs from multiple people and are more relevant for the topic of collaborative design.

In order to reflect the challenges faced by OSH products in terms of documentation, the methodological approach pursued in this article is to focus on the most challenging range of products. The underlying assumption is that "who can do more can do less", so what applies to complex non-electronic hardware applies also to more electronic hardware and simple products. As a consequence, this article specifically focuses on the recent evolution of the open source movement outside the domain of electronics and DIY to those of non-electronic and complex OSH products. It excludes the field of purely electronic hardware products. Not only is this methodological choice in consistency with the academic background of the authors situated in mechanical engineering and collaborative engineering design; it is also in line with the most recent advancement of the open source concept on forms of hardware which are in the sphere of influence in these disciplines. It should be borne in mind that the huge achievements of the still much larger open electronic hardware field have paved the way for this development. In no way is the exclusion of this field in this study an indicator of its irrelevance. Rather it is a matter of limiting the extent of the research undertaking.

As a result of this position, in the rest of the paper, "open source hardware" is used to refer to complex, non-electronic OSH.

4.2 Product selection

In contrast to previous research works aiming at grasping the contours of a phenomenon related to open source e.g. sharing of 3D-printed designs (see Kyriakou, Nickerson, and Sabnis 2017), no major centralised online entry point exists which aggregates relevant products in the context of OSH. While platforms such as GitHub™,[7] or Thingiverse™,[8] are playing this role for free and open source software or 3D-printing communities, to date, there is no generally acknowledged and widely used online platform supporting open source product development. These observations have been respectively made by Raasch and Herstatt (2011) and Howard et al.

(2012) and are still valid. On the contrary, projects developing OSH products tend to use a wide variety of tools for collaboration and dissemination (Bonvoisin et al. 2017).

As a result, OSH products have been identified using conventional internet search engines using a snowball effect approach. The results of this search have been screened through a restrictive criteria set in order to ensure a conservative evaluation of the phenomenon to be studied and to keep a deliberately narrow focus within the highly diverse field of open source innovation (see for example Ehls 2015 on that topic). The following selection criteria have been applied:

- The product is the outcome of discrete manufacturing. Products of food and process industries such as yoghurt, cement, chemicals or plastic compounds are excluded.
- The product contains at least *in-house*, tangible and non-electronic hardware, which includes mechanical or any other type of non-electronic physical elements (e.g. textile). It may eventually include electronic hardware and consequently software. Purely electronic hardware or software products such as Arduino or Linux are therefore excluded. In-house means that the piece of non-electronic hardware is 'original equipment' created by the product originator and not a component bought off the shelf.
- The product is complex. While well-defined metrics assessing product complexity on a positive real scale have been proposed in the scientific literature (e.g. Rodriguez-Toro, Jared, and Swift 2002), using those metrics requires having sufficient access to detailed data such as the number of parts. This condition is difficult to satisfy in the context of observation of partly documented and defined products. Therefore, in the following analysis, the complexity of products is evaluated with a rule of thumb: products are considered as complex if they consist of more than two parts of different materials. Products such as business card holders or cell phone cases or other 3D-printed gimmicks are out of scope. The objective here is to bring to the foreground those open source products that are on the upper side of the complexity scale. In other words, to select the few complex ones and let aside the myriad of gimmicks that can be found on CAD file exchange platforms such as Thingiverse or Shapeways.
- The product is developed for functional rather than aesthetic purposes. Jewellery, artistic and decorative items do not fulfil this criterion and therefore were not included.
- The product is at least partly defined, i.e. is provided with sufficient documentation to indicate that the product development maturity is equivalent or above the stage "system-level design" of the product development process as defined by Ulrich and Eppinger (2011). Undeveloped product concepts are not considered. Thus, the focus delineates from challenge platforms, which focus solely on capturing concepts from external participants.

- The product is labelled by its surrounding community as open source. The terms "open source", "open source hardware" or "open hardware" are used in the published documentation as an adjective to qualify either the product or the activities around the product. This is quite a conservative criterion. A non-negligible number of projects adopt principles of OSH without necessarily fitting neatly into this conservative criterion.
- There are no systematic 1:1 relations between product, project and community. For example, a community may be involved in more than one project and a project may involve the development of more than one product. However, in order to simplify the analysis, only one product per project and per community has been considered.

4.3 Data acquisition

For each of the selected products, two sets of descriptive criteria are defined. These are summarized in **Table 1**. The first set is dedicated to the characterization of the published product-related information. It translates in measurable terms the best practices of OSH as provided by the Open Source Hardware Association (2013) and complemented by a practice review performed prior to the reported research (Bonvoisin and Schmidt 2017a). In the absence of practicable indicators for assessing the quantity, the quality or the relevance of a piece of information, simple binary criteria are used, which indicate the presence or the absence of a given piece of information or of a given property. The second set delivers contextual information about the product, the corresponding development project, as well as the surrounding product development community.

Criteria are evaluated based on information that can be accessed through the websites of the product development communities. For the four criteria "CAD files available", "assembly instructions available", "bill of materials available" and "guidelines for participation", the following practical cut-off rule is applied for each binary criterion: If the necessary information to satisfy a criterion cannot be found in less than ten minutes, it is considered unavailable. This cut-off rule is consistent with the fact that accessibility to documents required by the Open Source Definition implies not only that these documents can be accessed, but also that they can be found easily.

Note that with the focus of the study depicted in section 4.1 "Focus: complex non-electronic hardware products", solely the documentation relative to the non-electronic hardware has been assessed. Documentation regarding electronic hardware and software has not been regarded. The authors emphasize here that this does not mean that the openness of electronic hardware has lower relevance in general. This methodological choice is rather dictated by the background of the authors and the willingness to limit volume of data to be gathered in this study. This attempt is based on the assumption that data gathered for non-electronic hardware are representative for data about electronic hardware.

Table 1: Open source hardware product characterization criteria.

Ref.	Name	Description
Part I − **criteria regarding shared product-related documentation**		
a	CAD files available	Boolean value indicating whether CAD files or schematics of the non-electronic hardware are available online.
b	CAD files editable	Boolean value indicating whether the online released CAD files of the product are editable. CAD files are considered editable if they are released in their original format. They are not considered editable if they are only released in an export format such as PDF or STL which does not allow further modifications.
c	Assembly instructions available	Boolean value indicating whether instructions for building the non-electronic hardware are available online.
d	Assembly instructions editable	Boolean value indicating whether the published assembly instructions are editable. Assembly instructions are considered editable if they can be edited in a web 2.0 environment or downloaded as editable files. A file is furthermore considered editable if it is released in its original format. It is not considered as editable if it is only available in an export format such as PDF.
e	Bill of materials available	Boolean value indicating whether a bill of materials relative to the non-electronic hardware is available online.
f	Bill of materials editable	Boolean value indicating whether the published bill of materials is editable. A bill of materials is considered editable if it can be edited in a web. 2.0 environment or downloaded as an editable file. A file is furthermore considered editable if it is released in the original format. It is not considered editable if it is only available in an export format such as PDF.
g	Guidelines for participation	Boolean value indicating whether guidelines for participation or a dedicated call for contribution are provided to potential contributors.
h	Commercial usage allowed	Boolean value indicating whether the licence applied to the non-electronic hardware allows commercial usage of the published content. If no licence is applied, the criterion is set to false.
Part II − **criteria regarding contextual information**		
i	Licence	Licensing scheme used for the publication of the non-electronic hardware.
j	Contains electronics	Boolean value indicating whether the product contains electronic hardware components as well.
k	Maturity	Defines the maximum maturity level achieved by one of the eventual versions of the product over time. Five maturity levels are defined in the order of increasing liability risk: 1. *Design.* There is only a theoretical design that is still to be fully developed. No liability of the product originator applies. 2. *Prototype.* The early design phases have been completed and the first functional prototype has been built. No liability of the product originator applies. 3. *Production/DIY.* The product is fully defined and documented and can be replicated. No liability of the product originator applies. 4. *Production/Kit.* The product is sold by a commercial actor as a kit. Limited availability applies to the vendor. 5. *Production/full product.* The product is sold by a company as a finished product. Full availability applies to the vendor.
l	Status of the community	Binary value indicating whether the community is active. The community is considered inactive in case no activity (encompassing either product development or sales and marketing) can be detected on the website or the collaboration platforms within one year.
m	Product category	Classification of the products in product groups.

Also, this article specifically focuses on OSH *development*. The *use* of OSH may require pieces of documentation which are not considered here, such as operating instructions and parts specifications. Withholding this information may render a product useless or even unsafe. The provision of operating instructions is for this reason legally requested in specific product branches such as automobile. As a consequence, the provision of operational instructions has not been considered as a distinctive characteristic of OSH in this article.

4.4 Openness assessment criteria
Based on the data defined in previous sections, four composite criteria are defined for assessing the compliance of the product-related documentation to the four factors of openness:

- The *transparency* (*T*) criterion addresses the freedom to study. A product satisfies this criterion when CAD files are published.
- The *accessibility* (*A*) criterion addresses the freedom to modify. A product satisfies this criterion when all published content is editable or when a guideline for participation is available.
- The *replicability* (*R*) criterion addresses the freedom to make. A product satisfies this criterion when assembly instructions and bill of materials are available.
- The *commercial usability* (*C*) criterion addresses the freedom to distribute. A product satisfies this criterion when licences applied to the non-electronic hardware allow commercial usage of the published content.

The four criteria are defined as logical operations on the Boolean values [a,...,h] as depicted by equation 1:

$$\begin{cases} T = a \\ A = \big((a \vee c \vee e) \wedge (a \rightarrow b) \wedge (c \rightarrow d) \wedge (e \rightarrow f)\big) \vee g \\ R = c \wedge e \\ C = h \end{cases} \quad (1)$$

In addition to this, a global *openness index* (*OI*) is defined as a cumulative point system. A product gets one point each time one of the criteria a, b, c, d, e, f, g, and h is satisfied. An openness index equal to 8 means the product fully satisfies the best practices of OSH. An openness index equal to 0 means the product satisfies none of the criteria defining OSH. The openness index is defined in equation 2:

$$OI = \Gamma(a) + \Gamma(b) + \Gamma(c) + \Gamma(d) + \Gamma(e)$$
$$+ \Gamma(f) + \Gamma(g) + \Gamma(h)$$
$$where \, \Gamma(x) = \begin{cases} 1 \, if \, x \\ 0 \, if \, \neg x \end{cases} \quad (2)$$

4.5 Clustering

In order to identify typical patterns in the publication of product-related documentation, products are clustered according to the values of the eight binary criteria [a,...,h] defined above. The k-medioids algorithm (or PAM, Partitioning Around Medioids) has been used since it is particularly adapted to the clustering of objects described by categorical data. This method requires as input an $n*n$ matrix giving a measure of the similarity of each pair of product. Each product is represented by a binary word of 8 bits—each bit representing a criterion from a to h (as described in equation 3). Inter-product similarity is computed according to the Manhattan distance (Choi, Cha, and Tappert 2010) of the products' descriptive 8-bit words as described in equation 4. The k-medioids algorithm requires also as parameter the number of clusters to be defined. The optimal number of clusters—so that adding another cluster does not provide further information—is calculated with the help of the elbow method (Tibshirani, Walther, and Hastie 2001).

$$P_i = a_i, ..., h_i \quad (3)$$

Where:

- P_i is a 8-bit word representing the product i;
- a_i, ..., h_i are the binary values of criteria a to h evaluated for product i.

$$S_{ij} = \sum_{k=1}^{8} \Gamma\big((P_{i,k} \wedge \neg P_{j,k}) \vee (\neg P_{i,k} \wedge P_{j,k})\big) \quad (4)$$

Where:

- S_{ij} is the Manhattan distance of binary words P_i and P_j and is a numerical of [0, 8]. A distance of 0 means words are equal. A distance of 8 means words are completely different.
- $P_{i,k}$ and $P_{j,k}$ are respectively the kth bit of words P_i and P_j;
- Γ is the function defined in equation 2.

5 Results

A data acquisition campaign was carried out between March 2016 and April 2017. This large time period ensured sufficient exhaustiveness of the snow-ball research. At the same time, it generated risks of data obsolescence. Therefore, the gathered data set was screened and actualized in its entirety in a last verification pass performed May 2017. In total, 132 products were found which satisfied the conservative selection criteria. Further modifications of the considered objects of research that occurred after May 2017 were not considered and are not reported in this article.

5.1 Pool of gathered products

The selected products cover a wide range of categories. The largest categories represented are machine tools (33 products), vehicles (18 products), robotics (11 products) as well as medical and laboratory equipment (9 products each, **Figure 2a**). The category *machine-tools* includes mainly desktop machine tools such as the 3D printer Ultimaker[9] or the laser cutter Lasersaur.[10] The category *vehicles* mainly consists of bikes like XYZ Space Frame Vehicles[11] and cars like the Tabby OSVehicle.[12] The category *robotics* is largely represented by humanoid robots developed for teaching or research purposes, such as the igus™ Humanoid Open Platform.[13] Finally, the category *medical equipment* covers diverse products like OpenBionics' Prosthetic Hand[14] or diagnostic equipment such as the echo-stethoscope echOpen.[15]

In total, a share of 43% of these (57 products) consist exclusively of non-electronic components. The remaining share of 57% (75 products) also comprise electronic hardware as well as software (**Figure 2b**). Three quarters of the products are currently developed and/or marketed; while other products originate from projects which are not active anymore (**Figure 2b**).

The distribution of products per maturity level depicted in **Figure 3** indicates that the majority of the selected products has reached a stage of development that enables systematic replication and production: 70% are in production stages.

5.2 Overall openness of the published documentation

Figure 4 depicts the number of products satisfying the criteria a to h as well as the distribution of products along the openness index (*OI*). The most satisfied criterion is the publication of CAD files (criterion a, with 77%, 102/132) and the least satisfied are the publication of a call for contribution and the editability of assembly instructions (criterion g and d, with respectively 26% and 25%, 34 and 33/132). In total, 11 products satisfy all criteria [a,...,h] while 10 products satisfy none of them. The arithmetic mean of the openness index of all products is 4.2 points (median value 4 points). **Figure 5** shows the number
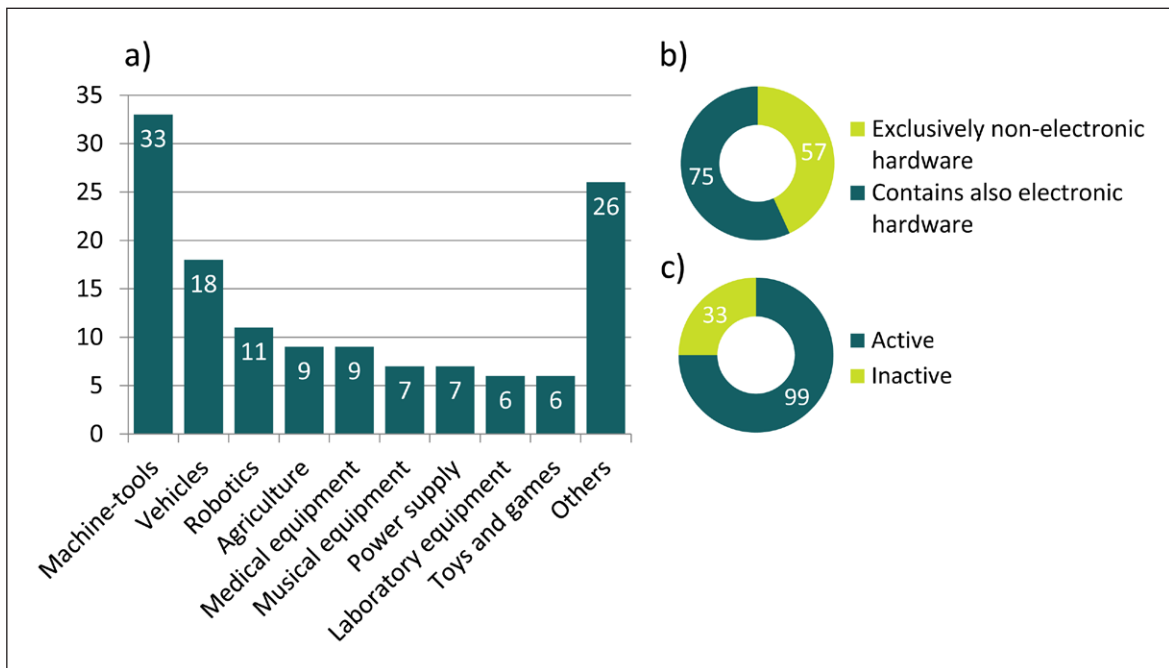
Bonvoisin et al: What is the "Source" of Open Source Hardware?

Art. 5, pp. 9 of 18

Figure 2: Characterization per product category **(a)**, per technology **(b)** and per project status **(c)**.
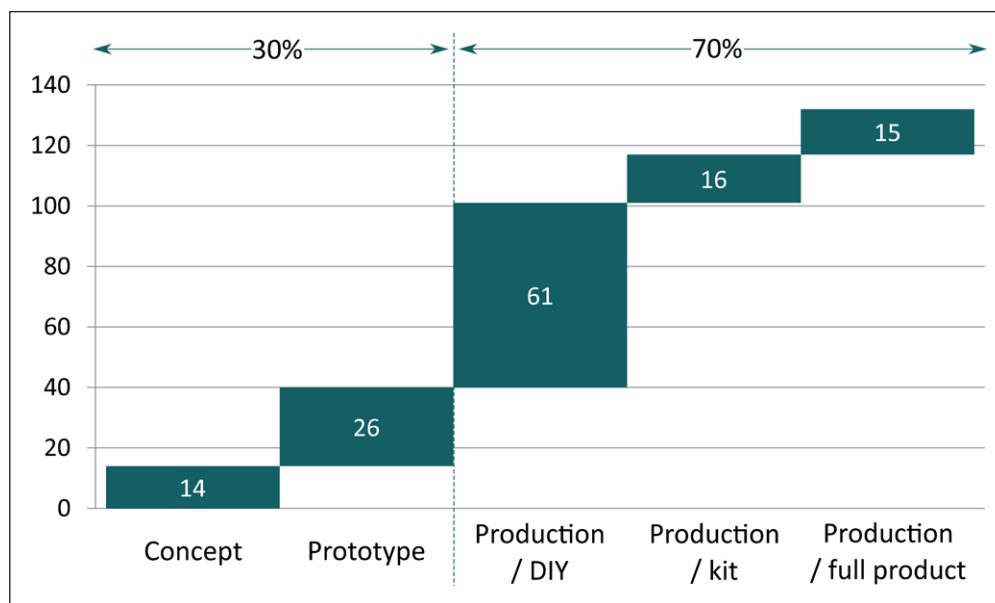

Figure 3: Distribution of products per maturity level.

of products satisfying the four criteria of openness (T, A, R and C). The most satisfied criterion is transparency (T, 77%, 102/132), respectively followed by commercial usability (C, 72%, 95/132), replicability (R, 60%, 80/132) and accessibility (A, 41%, 54/132). In total, 22 products comply with all the four criteria while 11 others fulfil none of them. The average number of criteria fulfilled is 2.5 (median value 3).

This data highlights a certain heterogeneity of practices in the publication of OSH product documentation. The large spectrum of openness observed tends to indicate that the different factors of openness are considered by practitioners more as optional factors rather than mandatory ones. On one side of the spectrum, a few products can be considered as fully open, because they satisfy the four criteria of openness (17%, 22/132) or get the maximal openness index (11%, 15/132). On the other side of the spectrum, another few products can be considered as fully closed, as they either do not satisfy any of the four criteria of openness (8%, 10/132) or get a null openness index (8%, 11/132). Between those extremes, the large majority of products show diverse profiles of partial openness without clearly identifiable patterns.

5.3 Relative frequency of openness factors
Results provided by **Figure 4** suggest that transparency and commercial usability may be aspects which are given high importance on average or which are easily achievable,
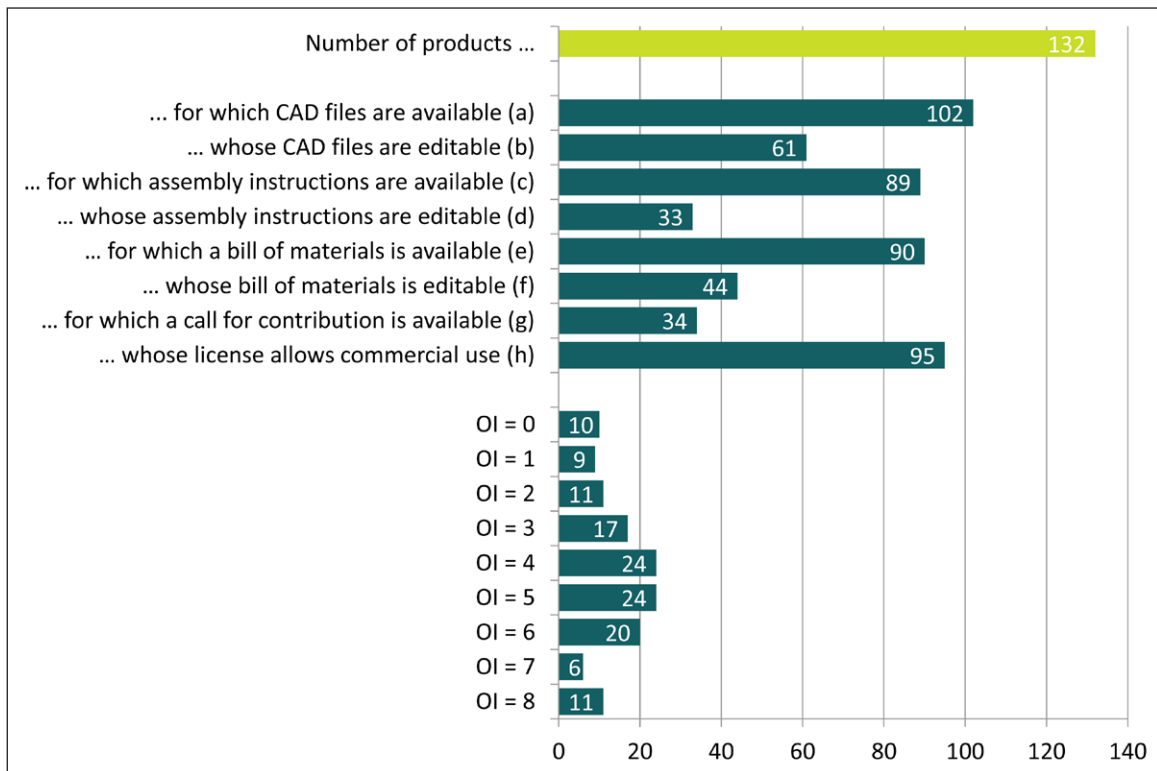
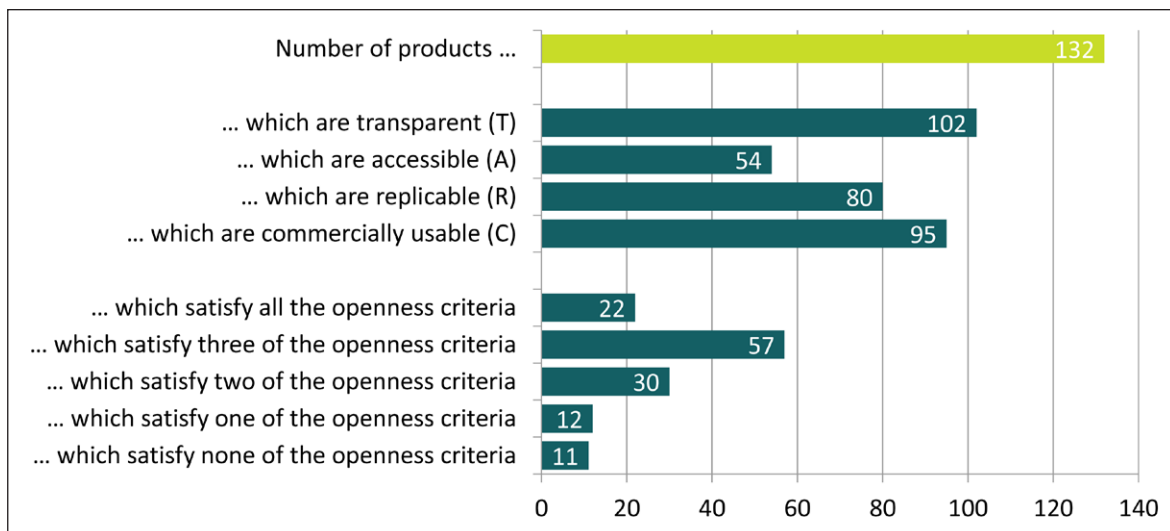**Figure 4:** Number of products satisfying the criteria a to h.

Figure 5: Number of products satisfying the criteria T, A, R and C.

while accessibility is an aspect which may be given low importance on average or difficult to achieve.

Transparency is not associated with high additional costs, as it is related to the publication of files which are required in the development process (CAD files and schematics). Nonetheless, a significant number of products (almost one fourth) are not providing these files publicly.

Commercial usability is related to IP risks. The commercial usability aspect is at the core of the concept of open source, still, more than one third of the products are not provided with a licence allowing commercial usage or are published under licences excluding commercial usage. In the latter case, these products are actually unambiguously

not complying with the Open Source Hardware Statement of Principles 1.0 which requires explicitly the use of licences allowing commercial usability.

The lower occurrence rate of replicability may be explained by the corresponding additional effort. Indeed, it requires more resources to make a product replicable than transparent or commercially usable. Furthermore, while transparency is about sharing files which are required for the development process of the product and exist whether or not the product is open source, replicability requires the formalization of assembly instructions and bill of materials, which is a time intensive activity. Not all communities may be willing to make the

effort to formalize these documents. Moreover, assembly instructions may only be relevant for products which are meant to be produced in a DIY production setting. In the context of projects dedicated to the development of complex OSH products which are meant for industrial production, assembly instructions may be secondary or even irrelevant information.

The lower occurrence rate of accessibility may also be explained by the corresponding additional effort. As introduced earlier, accessibility is a precondition for the emergence of a community-based co-development process. Integrating contributions from a development community implies significant coordination costs and requires dedicated resources. As accessibility supports a process which is difficult to implement in practice, not all product originators may give this aspect a high priority.

5.4 Role of contextual criteria in openness

Table 2 compares the openness of all products categorized along three assessed contextual criteria: product maturity, whether products are purely mechanical or mechatronic, and whether the surrounding community is active or inactive.

A first possible reason for the absence of published documentation may be that this documentation does not exist and cannot exist in the level of detail required by the criterion used here. Indeed, in early design stages, the product documentation may not be mature enough for the product concept to be formalized into CAD files, assembly instructions and bills of materials. This explanation tends to be supported by the gathered data, as the average openness index of products in the early phases (concept and prototype) is significantly lower than those of production phases (DIY, kit, full product production). The percentage of products satisfying the criterion of transparency grows along with product maturity: it is lower than 54% in the concept and prototype phases and grows over 89% in the other phases. The average openness index increases as well, however, it starts to sink again at the last stage (full product production) due to lower replicability

and commercial reusability. In this phase products are marketed by companies which are taking financial risks. This may make them hesitant to disclose information that facilitates imitation.

A second possible reason for the absence of published documentation may be that the community which drove the product development is not active anymore. In that case there is not enough workforce anymore to maintain data online; links become "dead links" and information finally disappears. This explanation tends to be supported by the gathered data, as the average openness index is significantly higher for products with active surrounding communities than for products with inactive communities (respectively 4.57 points and 2.91 points).

A third possible reason for the absence of published documentation may be that the community which drives the product development does not follow an open source approach for the entire product but only for selected components. A straightforward case is when products include off-the-shelf components which are not open source. Another case is when originators deliberately exclude a developed component from the open source approach in order to protect their strategic knowledge. This behaviour has been previously empirically observed and is discussed by Balka, Raasch, and Herstatt (2014). It is however explicitly excluded by the Open Source Hardware Certification Programme of the Open Source Hardware Association as it is claimed that "all parts, designs, code, and rights under the control of the creator must be made open" (Open Source Hardware Association 2017). In the current study only the openness of mechanical components has been assessed and those of software and electronic hardware components contained in mechatronic products have been left aside. It is therefore possible that a mechatronic product appears here as non-open although the corresponding electronic hardware and software are open source. Following this explanation, there would be a high chance that the average openness of mechanical parts of mechatronic products should be lower than those of purely mechanical products. This explanation is

Table 2: Openness vs. contextual criteria.

	Number of products	OI	Transparency		Accessibliity		Replicability		Commercial usability	
		Mean value	Absolute	Relative	Absolute	Relative	Absolute	Relative	Absolute	Relative
Concept	14	1.64	4	29%	6	43%	1	7%	7	50%
Prototype	26	2.54	14	54%	10	38%	6	23%	16	62%
Production/DIY	61	4.93	54	89%	26	43%	48	79%	46	75%
Production/kit	16	5.38	15	94%	4	25%	15	94%	14	88%
Production/full product	15	4.80	15	100%	8	53%	10	67%	12	80%
Mechanic	57	3.65	38	67%	25	44%	30	53%	39	68%
Mechatronic	75	4.53	64	85%	29	39%	50	67%	56	75%
Active	99	4.57	83	84%	46	46%	67	68%	76	77%
Inactive	33	2.91	19	58%	8	24%	13	39%	19	58%

however not supported by the gathered data, as the average openness index is higher for mechatronic products than for purely mechanical products.

The following other possible interpretations of the absence of published documentation cannot be verified by the data gathered in this article:

· The intention of openness is given in the product development project, but the project lacks capacity to document and to put the product-related documentation online. Although in open source communities publishing documentation is seen as a way to gather new workforce, generating product documentation remains a time-consuming process and may get lower priority than other product development activities.
· There is a certain delay between the statement that the product is open source and the actual disclosure of product-related information. Project initiators may start claiming a product is open source before the corresponding documentation is put online.
· The product is claimed to be open source whereas no intention to publish product-related information is given in the product development project, what we can term here as "openwashing" in analogy to "greenwashing" or "whitewashing".

5.5 Typical profiles
In order to identify possible typical profiles, the k-medioids algorithm has been computed on the dataset leading to the identification of five clusters. The similarity matrix reordered according to the identified clusters is displayed in **Figure 6**. The openness of the products of each cluster is displayed in **Table 3** and described hereafter:

· Cluster 1. Fully open products which satisfy almost all openness criteria and having hence a high average OI value (mean value 6.83/8).
· Cluster 2 and 3. Products being transparent, replicable and commercially usable but not accessible. Their average OI value is medium to high (mean value respectively 5.23 and 3.81/8) and is mainly handicapped by the lack of accessibility.
· Cluster 4. Products being transparent, accessible and commercially usable but not replicable. Their average OI value is medium to low (mean value 2.94/8) and is mainly handicapped by the lack of replicability.
· Cluster 5. Fully closed products, i.e products for which almost no documentation can be found and out of which two thirds do not provide commercially usable documentation. Their average OI value is very low (mean value 0.83/8).

Apart from products showing full or near zero openness (C1 and C5), this clustering displays two other profiles: products developed in the frame of projects thriving at all openness aspects excluding accessibility (C2 and C3), and products developed in the frame of projects thriving at all openness aspects excluding replicability (C4). These results tend to highlight the existence of two OSH project archetypes: the one using openness as a way to support the emergence of collaborative development in communities, the other using openness as a way to support the broad diffusion of the outcome of a conventional and closed product development process. Cluster C1 can be interpreted as a combination of these two archetypes, i.e. as projects of C4 which achieved the product development phase, reached the production and commercialisation phase and started to strive for replicability.

6 Discussion
What emerges from the analysed data is a multifaceted picture of OSH which confirms the existence of a "confusion on what actually makes a project an open source
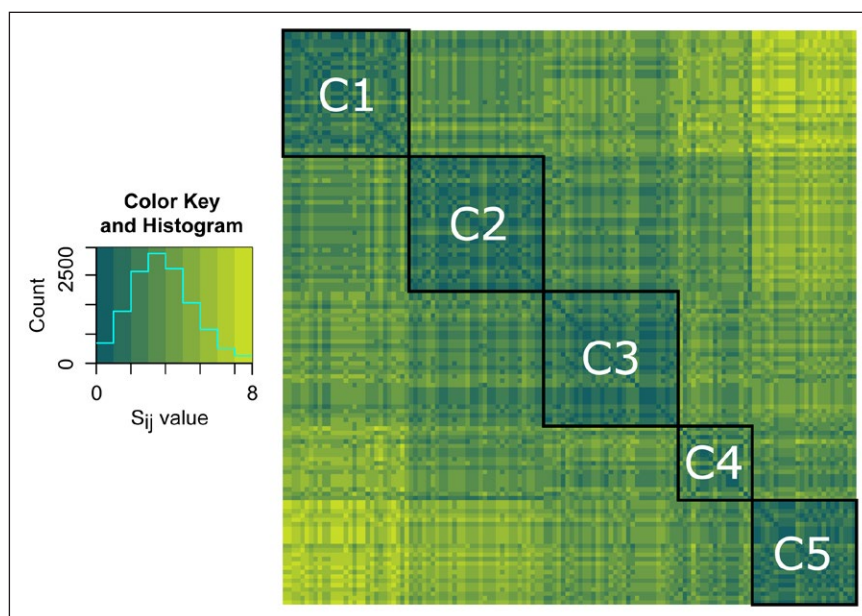

Figure 6: Heatmap representing the Manhattan distance S_{ij} between each pair of the 132 products (dark green pairs are similar, light green are dissimilar).

Bonvoisin et al: What is the "Source" of Open Source Hardware?

Art. 5, pp. 13 of 18

project" identified by Gacek and Arief (2004) in the field of OSS. Product originators tend to make use of the large room for interpretation given by the fuzzy definition of the term "open source hardware", to pick up the openness factors best fitting with their situation and therefore to answer for themselves the question "what is the source of open source hardware?" in different ways.

Whereas none of the four openness factors are represented by more than three fourths of the gathered products, the two factors *transparency* and *commercial usability* are nonetheless considered mandatory by most practitioners. The respective non-compliance rates of 23% and 28% may be considered as a normal and reasonable gap between theory and practice. Transparency is the most represented openness factor and the non-compliance to this factor can be largely explained by the fact that some products are not mature enough for CAD files to be produced and published. Commercial usability can simply be considered as mandatory as it is the only factor of openness explicitly addressed in both the Open Source Definition and the Open Source Hardware Statement of Principles 1.0. Furthermore, it can be viewed as a prerequisite to *flank* transparency.

The somewhat optional nature of the two other openness factors *accessibility* and *replicability* bases the identification of two main product development project archetypes in OSH. One makes use of open source publication of product-related documentation as a means to support community-based product development, while the other makes use of these same means for supporting diffusion of their privately developed product. Interestingly, projects of the first group are less numerous than those of the second group. These results are in contradiction with the general use of the term "open source" as a depiction of a collaborative product development process (as said in e.g. Gacek and Arief 2004).

6.1 Framing the "source" of open source hardware

It appears from the reported analysis that the "source" of OSH tends to be interpreted in practice as a dataset whose contents and properties evolve along the product lifecycle. This is summarized in the *open source hardware lifecycle* depicted in **Figure 7**. This original framework defines two states of OSH characterized by specific motivations and shared product documentation as well as two modes for developing open source hardware products. It also specifies in more detail the concepts which contours have been previously defined in scholarly contributions.

Within the product development process, an open source approach may be used as a means to support the emergence of community-based product development. The OSH product is then before all the object of an *open source product development* process (state 1 in **Figure 7**). In order to be labelled as "open source", this process requires at least commercial usability, transparency and accessibility. At early development stages, transparency can only be realized through the publication of descriptive text and simple schematics. Along the development of the product,

Table 3: Openness of the four identified clusters.

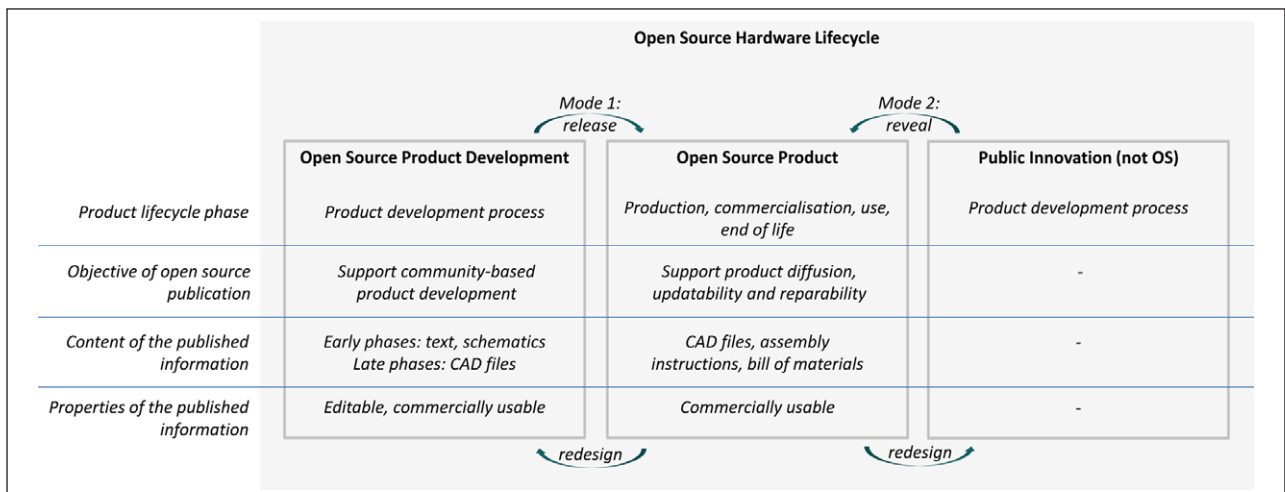| Cluster	Number of products	OI	Transparency		Accessibility		Replicability		Commercial usability	
		Mean value	Absolute	Relative	Absolute	Relative	Absolute	Relative	Absolute	Relative
C1	29	6.83	26	90%	24	83%	28	97%	24	83%
C2	31	5.23	31	100%	7	23%	27	87%	26	84%
C3	31	3.81	28	90%	5	16%	25	81%	24	77%
C4	17	2.94	15	88%	10	59%	0	0%	13	76%
C5	24	0.83	2	8%	8	33%	0	0%	8	33%

Figure 7: Open source hardware lifecycle.

stable technical drawings emerge (CAD files) which have to be shared in order to support further collaborative development. Accessibility is ensured by the use of editable formats (e.g. native and open CAD formats instead of STL files, native and open text editor files instead of PDF files).

Once a product is fully defined and can be produced, it can be documented as an *open source product* (state 2 in **Figure 7**). In this case, open source is used to support the production and diffusion of the product and its durability (through reparability, modifiability and upgradability). In order to be labelled as "open source", this product can be delivered with additional information, such as bill of materials and assembly instructions, which support production. Making use of this information for actual production and commercialization purposes requires this content to be published with licences allowing commercial usage. During the usage phase and at the product end-of-life, access to this same information may support the aspects of durability mentioned above.

An open source product can either be the result of an open source product development process (mode 1 in **Figure 7**) or of the disclosing of documentation developed in a private setting—defined as *public innovation* (mode 2 in **Figure 7**) by Huizingh (2011). Note that the latter is not an open source development approach, because it neither supports accessibility nor transparency. Upon the release of an open source product, the basis is made for new versions to be developed within any one of the two modes. Once a new version of an open source product is released it becomes the basis for further continuous open source product development or public innovation within a private innovation process.

The state "open source product development" has been previously termed in literature as *open source innovation* (Huizingh 2011; Raasch, Herstatt, and Balka 2009) and as *open design* (Balka, Raasch, and Herstatt 2009; Aitamurto, Holland, and Hussain 2015). The state "open source product" is the result of either *open source innovation* or *public innovation* as termed by Huizingh (2011). The lifecycle model is consequently in contradiction to an exclusive definition of OSH as a subcategory of open source innovation, as defined by Raasch, Herstatt, and Balka (2009) as well as Huizingh (2011). This would omit a large part of the actual practices rightly claiming the label of "open source hardware", which also includes the free revealing of innovations achieved in private settings. In those cases, however, labelling the product as open source would only make sense after a public release. An open source product development project as defined here may already fulfil the necessary requirements earlier.

6.2 Limits of the reported research
The list of OSH products gathered for this study cannot be claimed to be exhaustive and its representativeness for the entire field of OSH has to be considered cautiously. The authors also cannot exclude that the method used to search for eligible products may have omitted subsets of the field. Particularly product development projects which are in the early development phases may be more

difficult to find because they are still poorly documented and their communities are relatively small, if there is any at all yet. This may be the same for projects which acquired low publicity and are therefore poorly ranked in common internet search engines. Nonetheless, the list of OSH products gathered for this study, with this focus, is the largest that has been published so far. At the time the data acquisition campaign was terminated (April 2017), the marginal search time for finding a new project was high enough to justify freezing the dataset since the risk of omitting a significant part of the studied phenomenon was reasonably low.

Additionally, the broad field of OSH was narrowed down to discrete, tangible, non-electronic and complex products, which excludes a large part of the field (such as millions of gimmicks). In terms of how far the results discussed in this article are valid for the whole range of OSH products, including low complexity products as well as purely electronic products, remains an open question. Further research could make use of the methods defined in this article in order to perform a similar analysis specifically addressing electronic hardware. To the knowledge of the authors, no such a study has been published so far. The OSHWA maintains a list of certified OSH products, most of which are electronic products, providing therefore an interesting data basis.

The assessment of the corresponding published product-related documentation has been simplified to the evaluation of binary criteria. Each product was assessed as to whether certain types of documents are provided. The quality of the published documentation with regard to the level of detail, comprehensiveness or clarity has not been examined. *Do published CAD files represent the whole product or just parts of it? Are the guidelines for participation easily understandable for potential participants and provide them with the right information? What information is displayed in parts lists and in what form?* These questions were not taken into account because of the need to reduce the data acquisition effort to a manageable level. This simplification may have produced a positive bias, whereby products may have been rated more open than they are. Future research is needed in order to define to what extent published product-related documentation is actually usable and useful.

On the other hand, the practical cut-off rule for each binary criterion may have introduced a negative bias. Products may have been rated less open than they are. Simply because some pieces of documentation have not been found after ten minutes of internet search, this does not necessarily mean that information cannot be found online. The cut-off rule applied is a practical interpretation of the Open Source Definition which requires that documents can be accessed "easily". Another negative bias comes from the fact that only information related to the non-electronic hardware components included in the respective products was evaluated. Documentation regarding electronic hardware and software has not been regarded as a practical cut-off in data acquisition (see Section 4.3 "Data acquisition"), hence, parts of openness have been omitted. Needless to say, the openness of electronical hardware is as important as those of

other types of hardware. Consequently, the openness of a mechatronic product should be assessed upon those of its electronical and mechanical components.

The dataset on which this article is based upon has been published with a CC-BY licence (Bonvoisin and Schmidt 2017b, http://doi.org/10.14279/depositonce-5977). An actualized version of this dataset is available under the same licensing terms in the Open Source Hardware Directory.[16] This database of complex OSH products allows any interested person to add references of OSH products, or to edit existing ones. The content of this database can be used for any purpose, such as future research as suggested in this article. The objective of the methodology pursued in this article and in the generation of the data was to generate an overview of the field of OSH. The authors cannot guarantee that the presented data of more than 2000 items is free of errors. Should the originators or contributors to the OSH products referenced in this dataset consider their products misrepresented, the authors kindly invite them to make corrections. They are free to edit the provided database or inform the authors of detected errors.

7 Conclusion

This article provides an overview of how the concept of OSH is interpreted in practice, in other words, what is the "source" of OSH for practitioners. Starting from a critical analysis of existing definitions, evaluation criteria have been defined and used to analyse the published documentation of a pool of 132 complex and non-electronic OSH products.

The gathered data illustrates how the field of OSH has moved well beyond the scope of electronic hardware, towards the field of non-electronic complex product development. The reported research required the establishment of a database of OSH products which is the largest published to date. This database provides empirical evidence of the evolution of OSH outside the sphere of electronics—a phenomenon which presently has only been described by scholarly publications based on isolated cases.

The analysis of the published documentation of the 132 identified OSH products confirms the wide range of documentation sharing practices which may also be due to the fuzzy definitions of OSH. Product documentation ranges from very demanding to very lax compliance, i.e. from the mere sharing of CAD files to the publication of comprehensive sets of documents. The results highlight a surprisingly large share of products which are provided with barely any information at all (cluster C5, 18%). This could either be due to a misinterpretation of the concept of OSH, a deliberate intention to "openwash" a product, or the influence of the time variable. What can be understood from this is that there is a need to set standards in order to achieve clarity in the field of OSH. This will support the emergence of a constructive public discourse around these new practices.

Clustering the characteristics of published product-related documentation led to the identification of two distinct states of OSH. These have been understood as resulting from differing though not mutually exclusive strategic modes: namely the stimulation of community-based product development and the public dissemination of privately achieved innovation. The interaction between those states has been summarized in the definition of an OSH lifecycle summarizing observed approaches to OSH. It is the hope of the authors that this article has introduced solid categories that have provided a foundation on which further practice and research activities can be based.

Notes

[1] For an overview of OSH licences see for example Katz (2012).
[2] Source: https://perma.cc/99TD-EB6P (accessed 06.06.2017) is a platform that allows to share a huge variety of 3D models based on CAD or STL files.
[3] Source: https://perma.cc/XZ7W-ELAQ (accessed 06.06.2017) is a network of makers that collaborate locally with disabled children to provide them with adapted 3D printed hand prosthesis.
[4] Evolutionary design may not generally contradict parallelization or staging of processes, i.e. in the intra-project environment for scaling and efficiency. Also, this is different to the predetermined mechanism of breaking down problems into constituent parts (modularization) and avoids creation of task interdependencies.
[5] These four freedoms are derived from the free software definition (Free Software Foundation 2015), which are: Freedom 0, the freedom to run the program for any purpose; Freedom 1, the freedom to study how the program works; Freedom 2, the freedom to redistribute copies; Freedom 3, the freedom to distribute copies of modified versions. In the transition from the context of immaterial intellectual property to the realm of tangible products, these freedoms have been reinterpreted. For example, running a programme requires compiling the source code (an action alternatively termed as build or make in the software jargon). The freedom to run became the freedom to make the product, that is, to produce it.
[6] For deeper insights into the different degrees of involvement in open source communities, see for example Gacek and Arief (2004).
[7] Source: https://github.com/.
[8] Source: https://www.thingiverse.com/.
[9] Source: https://ultimaker.com (accessed 30.01.2017).
[10] Source: http://echopen.org (accessed 30.01.2017).
[11] Source: https://perma.cc/7LXQ-PGKN (accessed 30.01.2017).
[12] Source: https://perma.cc/96W5-ND74 (accessed 30.01.2017).
[13] Source: http://www.nimbro.net/OP (accessed 30.01.2017).
[14] Source: https://perma.cc/N7Y2-J5YC (accessed 30.01.2017).
[15] Source: http://echopen.org (accessed 30.01.2017).
[16] Source: https://perma.cc/T9CS-UE28 (accessed 07.07.2017).

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Competing Interests

The authors have no competing interests to declare.

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Art. 5, pp. 18 of 18

Bonvoisin et al: What is the "Source" of Open Source Hardware?