OPEN SOURCE BEYOND SOFTWARE: RE-INVENT OPEN DESIGN ON COMMONS GROUNDS

Keywords:
Open Design, Open Source Hardware, Digital fabrication, Parametric Design, Digital Commons

ABSTRACT

Existing open source hardware (OSH) literature has focused to electronic or mechanical hardware but less is known for the OSH subset being neither electronic nor mechanical. We analyze bidirectionally the openness theoretical framework and the specific practices' subset through a set of case studies. Based on the ascertained limitations and existing tendencies of alternative design methodologies, we highlight an emerging open design (OD) direction with potentially instrumental dimension for the entire OSH field.

INTRODUCTION

Open source software (OSS) has become a dominant mode of production in a number of areas such as server software, operating systems and scripting languages (Lerner and Tirole, 2005: 99-100; Chesbrough and Appleyard, 2007: 64). Since the last decade, several studies have focused to a wider applicability (von Krogh and von Hippel, 2006; Nuvolari and Rullani, 2007: 227) of the OSS organizational and production model (von Hippel and von Krogh, 2003; Osterloh and Rota, 2007). Benkler draws from OSS and early P2P sharing networks to describe a third mode of production (2002: 375-376), the commons based peer production (CBPP) (2006: 59-90), extending beyond software to open content such as Wikipedia and Openstreetmap among others. Additionally, an equally important direction is the extension of the open source model to the world of tangible objects (Raasch et al., 2009; Balka et al., 2009a, 2009b; Shirky, 2005: 483).

Initially an important part of free and OSS theorists have objected or at least have been sceptical to the openness parallelization between bits and atoms (Stallman, 1999; Raymond, 1999a; Maurer and Scotchmer, 2006: 30; Ackermann, 2009:210). However, in the course of time the OSH's potential was realized as among other advantages, the OSH will represent the only possibility to run freely OSS in the near future (Stallman, 2015). In the meantime a lot of major open source hardware (OSH) projects have emerged. Indicatively, some of the most prominent approaches are located in the fields of:

- Mechatronics (RepRap, Arduino, OpenBionics)
- Architecture (Wikihouse, Open Architecture Network, Hexayurt)
- Agriculture (Farmhack, Ateliers Paysan, Open Source Ecology)
- Design (Opendesk, Openstructures).

Von Hippel makes a clear distinction of the immaterial phase or design "source code" of the OSH.

> *"Hardware is becoming much more like software up to the point you actually fabricate an object."* (Von Hippel in Thompson, 2008).

Lakhani describes a user-powered design innovation, proactively forcing companies out of the product design space (2007). In this sense the design activity is separated from manufacturing as a semi-autonomous knowledge intensive field pre-qualifying for immaterial CBPP. Furthermore, manufacturing is fading as a centralized, closed and capital intensive activity (Carson, 2010: 159, 219). Additionally, the digital fabrication and hackerculture have lead to the emergence of a rapidly increasing global network of local makerspaces (Niaros et al., 2017: 1145). Consequently, open design (OD) becomes the cornerstone of the OSH, forming a re-arranged communal type of design-construction continuum.

The article is structured as follows: In the next section we describe the existing theoretical framework of OSH and OD, as well as the stimulated research questions. Successively, the third section contains the research methodology and the case study analysis. The fourth section discusses the resulting limitations concerning both practices and theoretical framework and outlines an emergent OD direction based on the instrumental potential of parts of case study research. The final section provides a conclusion of research results along with directions for future elaboration.

LITERATURE REVIEW

The term OD does not imply a single and cohesive meaning (De Mul, 2011). In theory and practice it is often used interchangeably with different but frequently complementary meanings, such as the collaborative, cooperative or participatory design, the modular design or the freely shared design. Actually, all of those meanings represent major dimensions of an evolving OD definition in the framework of digital commons and digital fabrication.

Analytically, the Design Global, Manufacture Local (DGML) model (Kostakis et al., 2015) highlights a new productive model with transformative socio-economic implications that is based on the convergence of globally shared OD commons with desktop manufacturing. The voxel-based fabrication describes a modular design methodology along with an experimental manufacturing technique, which is based on the discourse between digital and analog materiality (Gershenfeld 2007, 2012; Gershenfeld et al., 2017; Kostakis and Papachristou, 2014a; Hiller and Lipson, 2009). Manzini (2015) draws a hybrid collaborative design model consisting of both expert design and diffuse design, based on social innovation or what Von Hippel (2017) later coined as collaborative free innovation. The earlier term user innovation (Von Hippel, 2005) refers exclusively to innovation by individual players for their own use (Von Hippel, 2017: 144).

Despite the existence of wide literature on various aspects of OSH and OD, there are very few attempts to provide a solid quantitative definition of openness in the discussed framework. In general the most systematic and comprehensive quantitative method up to date regarding openness evaluation is the open-o-meter [1]. Analytical documentation of the openness scale (Table 1) is presented by Bonvoisin, Mies, Boujut and Stark (2017).

It is important to trace open-o-meter history back. Open-o-meter is a further specification of theoretical principles (study, make, modify, distribute) and factors (transparency, replicability, accessibility) of openness referenced in Open Source Hardware Association's Statement of Principles 1.0 (2016) and Balka et al. (2010, 2014) respectively. Generally, the theoretical background of openness is borrowed from OSS theoretical principles. Successively in this way, Open Source Hardware Association's principles are based to the Open Source Definition (Open Source Initiative, 2007). Consequently, open-o-meter leans towards open source rather than free software political standpoint. As a logical extension open-o-meter values licences allowing commercial reuse as a basic parameter of openness. In fact there is a profound contradiction between commercial reusability and the notion of openness. Some of the most known examples of free software (GNU/Linux, Apache server, Mozzila Firefox) thrive in the absence of a licence allowing commercial appropriation. Additionally, there is evidence that openness (transparency, replicability and accessibility) affects the level of contribution (Balka et al., 2014) even if some forms of openness play a greater role than others.

> RQ1: Is the notion of openness well defined in the discussed framework, in analogy with the structural properties (Osterloh and Rota, 2007, Baldwin and Clark, 2006) of OSS development? In other words, is freely available and editable documentation as described by open-o-meter, necessary and sufficient condition to define a practice or a process as OD or OSH?

At this point, it should be stated that from an ideological point of view the author stands with the position of the Free Software Foundation (FSF), rather than that of Open Source Initiative (OSI), regarding the social imperative of software (Free Software Foundation, 2016). Since at the technical level, free software source code qualifies as open source code (Stallman, 2016) and vice versa, it could be supported that open source code is just one -the technical one- of the constituents of free software definition. In this sense, hereby the term open source code, OSS or open source design does not necessarily point to the OSI definition, unless otherwise explicitly stated. Additionally, taking into consideration the framework of this paper, OD is a commonly acceptable term, comparing with the limited usage of the term free design.

To get back on track, previous research works employing a quantitative assessment of openness have covered the field of IT hardware and electronic products (Balka et al., 2010, 2014), as well as the field of non-electronic but mechanical hardware (Bonvoisin et al., 2017). To the author's knowledge, there is no published quantitative study evaluating openness in the OSH subset that is neither electronic nor mechanical. It is explained by the initial lack of practices being neither electronic nor mechanical. Due to the proximity of electronic hardware with OSS movement, the first OSH projects were electronic devices (Gibb, 2014: xv). It is characteristic that TAPR - one of the first open hardware license - when released in early 2007, had considered only electrical or mechanical artifacts as potentially open hardware [2].

> RQ2: Are the openness criteria (Table 1) context-specific or generic? Do they need further specification according to each OSH's subset?

Stepping from OSH's content to context, we realize that it is meaningless to examine the OSH as an autonomous movement but only in a wider perspective as described by digital fabrication and CBPP. The digital fabrication revolution (Rifkin, 2014: 107-132; Hermann et al., 2016) makes feasible the distributed - even personal - manufacturing of a genealogy of custom objects, virtually at the same unit cost as if producing identical copies. Additionally, the open source model spreads out the software domain, successfully migrating to other fields of immaterial CBPP and forming global collaborative networks, despite the limitations of space and time. The promising convergence of peer production and desktop manufacturing had been described by Kostakis et al. (2013).

> RQ3: Are the OSH's contextual parameters taken into consideration to open-o-meter methodology? How are the advances in digital fabrication and the concept of CBPP reflected to openness evaluation criteria?

ASSESSMENT OF CURRENT PRACTICES

Research Approach and Methodology

In order to address the research questions mentioned above, we employed a hybrid empirical quantitative-qualitative case study research. Specifically, the quantitative part is concerned with the evaluation of openness levels in the selected OSH practices, as a supporting supplement to the rest of the research. The quantitative method of openess' assessment is the open-o-meter (Table 1), as documented by Bonvoisin et al. (2017). Despite the fact that the original openness scale utilizes only boolean value rating, the current research adopts the use of midpoint assessment, as a general measure for those cases where a variable pattern is discerned. This is the case for communities that do not follow top-down restrictions regarding the kind of documentation or license released. Furthermore, the open-o-meter method followed in this article refers solely to part 1 of the original method, as the external criteria consisting the part 2 table, are mostly constrained by the case study selection process.

The selection of OSH projects is not based on a platform built on purpose, but on an already existing online directory of OSH projects [3] maintained by Wikipedia. The online directory is a dynamic, bottom-up archive of the OSH projects, the launch of which mostly coincides with the recent history of the OSH development [4]. The following selection criteria were applied to the initial list in order to narrow the corpus of research according to the research questions:

- The hardware is neither electronic nor mechanical. As the first two fields are already evaluated regarding openness by Balka et al. (2010, 2014) and Bonvoisin et al. (2017) respectively, it is crucial to define the complementary subset in order to test the contextuality of the openness criteria. Additionally, electronic and mechanical devices usually include stardardized, ready-made and commercially available components to a great extent. Off-the-shelf components can limit the design and customization potential inherent to user-developed hardware. Moreover, the examined subset of the OSH is dictated by the background of the author in architectural design.

- Inactive communities are excluded. Evaluating inactive communities regarding openness is a task of limited value. Active communitites are considered those who have commited a new structure upload or even a minor edit in already uploaded documentation in 2018. This criterion aims to exclude those communities that practically cease activities after producing the first or a few functional prototypes.
- Premature communities and projects are also excluded. An arbitrarily set time limit of 4 years from startup is considered as a reasonable time interval that most OSH communities should have acquired a certain level of maturity if they are to do so. Another point of maturity is the production of at least one functional prototype product. Previous attempts (Bonvoisin et al, 2017) have taken into consideration immature communities among others, as shown by the fact that nearly 50% of the cases do not provide editable CAD files and almost 25% do not even publish CAD files. These results indicate either immature communities that could not be characterized as open source yet or products that do not include any custom parts. In any case, the scope of this paper is not to study the evolution of openness in the course of development of OSH projects but to evaluate the "source code" in relation to the discussed framework.
- The hardware should feature a minimum level of complexity. An assumption is made that adequately complex products are considered those featuring at least 5 parts or components. The above imposed criterion excludes from the pool online 3d printing repositories such as Thingiverse. 3D printing repositories are usually characterized by an individual approach. The rationale behind complexity constraint is that more complex objects force more collective product development. Peer production in its essence is synergistic rather than an individual modus operandi.

The OSH communities that satisfy the imposed criteria are: Wikihouse [5], Opendesk [6] and Openstructures [7]. Intentionally, the shortlisted cases are not representative of the whole range of the OSH scape, but they are examined as collective - instrumental case studies (Stake, 1995) able to offer a new understanding of OD in the OSH framework. Representativeness of the sample is valued as secondary to the potential for insight, concerning the kind of the central research questions. As the selection of cases is of critical importance in any type of case study research (Denzin and Lincoln, 2003: 151-155), the formal selection process and criteria actually reflect the author's strategy in a given context. Moreover, it is important to stress that the aim of the collective quantitative case study research is not to concentrate on a comparative analysis per se but to illustrate potentially different answers to the research questions.

Opendesk

Opendesk is a for-profit company, supporting an online platform that connects furniture designers with customers and local makers all over the world. It was founded in 2014, and part of the founders is part of the Wikihouse creators. Opendesk practice largely depends on DGML model as it is by definition a global platform for local making. Moreover, it is based completely on CNC manufacturing as all designs are assembled from flat cut wooden profiles. Most of the furniture overpass the assigned minimum complexity limit but features significantly less parts than other OSH projects, comprising from a few elements to some dozens of elements. Profit making comes from charging 30% of the manufacturing cost as a transaction fee every time a customer orders a piece of furniture. Apart from the transaction fee, there is a provision for a design fee which is calculated at

8% of the manufacturing cost. In any case, all of the furniture designs are freely available for personal fabrication and usage.

Opendesk project collects 4.5 out of 8 points in the openness scale (Table 2). Assembly instructions and bill of materials (BOM) are provided in non-editable formats, whereas contribution guide is rather vague and closed process. Furthermore, licensing does not follow a uniform pattern, featuring a variety from copyleft to licences allowing commercial appropriation. As the object of design is considerably smaller comparing to other OSH projects, the shortage of editable supporting documentation (assembly guide, BOM) is rendered less important than the absence of an open contribution process. The top-down enforced modus operandi of Opendesk is based on a standard and fixed relation between designer(s) and object of design, not formally allowing any collective optimization process, which is very common to every CBPP and OSS project. Actually, modifications are theoretically feasible but for personal use only, as there is not any open platform or any even informal process for forking and then merging back to master branch. To conclude, Opendesk's one way workflow is almost identical to the conventional closed design process, being characterized by a small scale closed design team or individual designer retaining a theoretical ownership (above formal licensing) over artifact by indirectly controlling the potential modifications. Apparently, this is related to the nature of the for-profit organization but it seriously affects the project's openness. It seems not rational to rate open contribution potential equally with the existence of editable BOM or other supplementary documentation. Is it open a project that just freely reveals the "source code" of the hardware but restricts users and other designers from contributing to it?

It could be supported that despite drawbacks, Opendesk still offers what is considered by open-o-meter the "source code" (editable CAD files and non-editable BOM and assembly instructions) which seems almost enough to study, make and modify the design. In other words, Opendesk may be hardly characterized as an OSI compatible but certainly FSF incompatible project, in analogy with software openness. In contrast, a detailed examination of the shared "source code" will reveal that it is indirectly but efficiently, restricting users and designers from altering the shared furniture designs even for personal use. The criterion regarding editable CAD files (Table 1) in practice seems a rather generic and abstract scheme. The limitation of the evaluation criterion does not lie only in the quality of CAD files, as suggested by Bonvoisin et al. (2017: 14) but to the nature of the CAD files. To further the argument, it is required to make a clear distinction between design and fabrication CAD files. The actual shared "source code" of Opendesk is mainly flat-cut drawings, intended for CNC manufacturing, which are provided in editable format. Fabrication files even in native file format are still a derivative of actual design files. It is self-evident that cut-out drawings (Figure 1) can not help neither to study, nor to modify the design but only to make it. There is no doubt that if personal resources were limitless, an expert could use the fabrication outline drawings and the assembly instructions to reverse-engineer the design CAD model but this can not be the case. Another important note, beyond the analytic distinction to design and fabrication CAD files, is that the cognitive process producing the latter from the former is of utmost importance regarding the OSH development and definitely subject of openness evaluation. To conclude, community is not only restricted from providing optimization feedback but it is generally constrained from studying and modifying.

Even the freedom to make should not be considered as a totally independent principle from studying and modifying an object. Specifically, the three principles are interconnected to a great extent in a synergistic manner as the full potential of making is achieved only if you are first of all able to study and modify. Otherwise, the DGML concept will be deducted to a simple model of distributed "mass production", negatively affecting the real potential of OD. It is less meaningful and underutilized to use a CNC or a 3d printer just as a medium to manufacture locally identical copies of what is used to be massively designed and produced.

OpenStructures

Openstructures began as a student project at Institute without Boundaries in 2006. In September 2009, Thomas Lommee designer and former student team member organized an exhibition, showcasing the concept and some initial prototypes, as well as an open call for the collaborative development of the project. Openstructures is an open modular system for hardware inspired by the modularity emerging in OSS development. The centerpiece of Openstructures system is OS grid (Figure 2), a shared geometrical grid, built up out of 4X4cm squares. OS grid is scalable and theoretically can be used to design from furniture to houses. Openstructures design commons are organized in parts, components and structures depending on the functional and relative position of each element in a posssible greater scheme.

The open modular system has the potential to [8]:

- Generate flexible and dynamic structures comparing to standardized types.
- Stimulate re-use cycles of various parts and components
- Enable collaborative (and thus exponential) innovation within hardware construction

According to open-o-meter scale, Openstructures is the less open project (Table 2) as the only steadily provided documentation is the contribution guide. Basic documentation as CAD files whether editable or not is provided occasionally and rarely. Supporting documentation as BOM or assembly guide is totally absent. Licensing does not follow a specific pattern.

Community is encouraged to participate either one or more of the following ways [8].

- Designing parts, components or structures according to the OpenStructures grid
- Trading designs online.
- Exchanging your experiences and ideas with others in order to improve the system.

The absence of basic documentation and the occassional sharing of design files, in addition to the open contibution guide as outlined above lead to the conclusion that Openstructures may intentionally operate as an open platform for new designs regarding parts, components or structures but at the same time precluding any modifications to already existing elements. Actually, each designer is permitted to modify only those elements that he has authored. In this sense, Openstructures share some basic deficiencies with Opendesk regarding the conventional design workflow, even if Opendesk is certainly more enclosed towards externalities. At least, in the case of Openstructures there is still an open platform with no hierachical control of what - new design - is published. But it should be noted that in CBPP framework, optimizing existing knowledge modules is equally or even more important from making new modules. Commons -with OSS being an eminent example- are structured more like work in progress (Raymond, 1999b), continuously optimizing according to envirionmental inputs rather than finished products. On the other hand, even if it is not explicitly referred, it seems that modular grid in relation to the imposed design classification (parts, components, structures) was planned as a kind of an indirect, as well as asynchronous collaboration and optimization method. For instance, an Openstructures' structure containing parts and components designed by other authors is indirectly collaborative and may be optimized or re-assembled each time a "lower-order" author modify his part or component. In fact, it has been proved rather complex and partially ineffective method as the greater percentage of structures are either compact or comprised by nested parts and components, designed by the same author, practically eliminating cooperative practices.

This observation may be useful for another insight to Openstructures workflow. Generally, Openstructures is characterized by two types of modularity. The first one is geometric modularity, imposed by the compulsory implementation of an OS modular grid. The interesting detail is that joints and connections are not fixed but custom for each case as long as respected the OS grid. In this sense, the geometrical modularity of OS is substantially different from the voxel-based design described by 3d printing pioneers as Hiller and Lipson (2009) and Gershenfeld (2007, 2012). The second type is a hierarchical modularity defined by the position of each element into a greater structure. The relation between elements is not equipotential but is organized in certain degrees of order, resembling a typical vertical hierarchy. The incapacity of Openstructures to produce actually collaborative complex objects despite the whealth pool of structures could be attributed to two possible explanations. Firstly, the discretization produced by geometrically modular systems grows exponentially, when joints are not predefined and standard. As a consequence the outcome tends to be approximately continuous, eradicating any parts' interoperability that may be caused by the modularity of the grid. Secondly, the hierarchical division of elements does not come to produce a multiplying modular effect. In other words the a posteriori design modularization of a structure to parts and components is an analytic rather than a synthetic principle with limited effect to potentially cooperative bottom-up build-ups. In any case, the collaborative modular assembly of parts and components is additionally precluded by the presented fact that most authors do not share the CAD design files with the community.

Furthermore the occasionally and rarely shared CAD files, are only the design files, whereas fabrication files are never shared. This renders almost impossible for potential users to fabricate complex structures with little or no effort. As a consequence, Openstructures fails to gather a user pool which would have provided useful feedback. Beta-testers and generally users are extremely valuable for digital commons even as the developers base (Shirky, 2008:237-243). Raymond (1999b) strengthens the argument:

> *"# 6 Treating your users as co-developers is your least-hassle route to rapid code improvement and effective debugging.*
> *The power of this effect is easy to underestimate. In fact, pretty well all of us in the open-source world drastically underestimated how well it would scale up with number of users and against system complexity, until Linus Torvalds showed us differently."*

Additionally, fabrication drawings are not derived from design files in a deterministic way. Each specific design can be materialised in an indeterminate number of ways. To conclude, design files are certainly integral elements as highlighted in the case of Opendesk but there is no doubt that fabrication files as well, should be considered indispensable part of the feedom to make. Moreover, the cognitive procedure going from design files to fabrication is of equal importance for the OSH as the design itself. An illustrative example regarding this workflow is the Wikihouse.

Wikihouse

Wikihouse is a non-profit foundation that was initiated in 2011 [9] and it is claimed to be an open source project that re-invents the way we make homes, taking advantage of distributed digital manufacturing. Since then, architects, builders and users had constructed wikihouses all over the world inspired from the basic Wikihouse prototype called microhouse. Microhouse ensures by definition an advanced level of complexity far from the imposed limit as well as the prerequisite of a neither electronic nor mechanical product. By its intentions declaration, Wikihouse draws a clear parallel between OSS and architectural design as *digital design allows every home to be designed as code; instantly customized to its site and user* [5]. Moreover, it is self-defined as a collaborative project *by everyone for everyone* following the DGML principle *share global*, *manufacture local*.

Wikihouse features a certain structure of common knowledge organized in *tools*, *technologies* and *types* going from smaller components to larger. *Types* are ready-designed building layouts incorporating *technologies* as subsystems which are manufactured and assembled using *tools*. *Microhouse* is a one bed house design, currently being the only *type* shared with the community. Available *technologies* include WREN chassis system and OWL internal door kit. The latter along with *tools* are components of limited impact to the CBPP process. On the other hand, WREN is an integral system for developing and sharing new Wikihouse *types* or modifying existing ones. Its main purpose is to automate analysis, subdivision and assemblage of 3-dimensional frame components (Figure 3) into flat cut panels, able to fit to medium sized CNC cutting beds, whereas retain their structural integrity. Though it seems a minor bit of information, CNC cutting bed is a crucial parameter separating personal or small scale distributed fabrication from heavy and centralized industrial systems. In the case of microhouse a CNC of approximately net 1200(W)x2500(L) mm is required, which is considered as an intermediate machinery, somewhere between desktop and industrial equipment. Consequently, we will assess openness levels separately for type and technologies as they do not share the same documentation. Digital repositories of *type* and *technologies* are maintained at Github [10].

Microhouse type is evaluated as the most advanced project in the openness scale (Table 2). According to open-o-meter *microhouse* scores 7/8 points, the only drawback being the lack of assembly instructions in editable format, which seems a minor deficiency comparing to other criteria. In other words, if open-o-meter is a thorough and reliable method for the assessment of OD then Wikihouse should be an almost perfectly open instance in-line with the principles of OSS development. Contrary to the expectations, microhouse development has considerable structural differences from well known OSS examples. Despite the fulfilment of open contribution guide criterion, the development of microhouse type remains largely at the control of a closed team mostly coinciding with Wikihouse founders. The microhouse repository at github [11] has 42commits from only 3 unique contributors. The initial commit was at the 25th of August of 2016 and most of the commits refer to supplementary documentation rather than design files. In other words, the repository was uploaded when the project was mature and most of the core files were already prepared by the founders. Since then, only minor edits have occurred. The above mentioned characteristics are very common to the early stages of OSS development before migrating to an open distributed and global mode of production. On the other hand, Wikihouse is a seven years old effort that could not be considered as an immature OSH project since among others it has produced at least one complex and functional prototype. Consequently, a published contribution guide along with editable CAD files, BOM and assembly manual may not be enough to promote accessibility and freedom to modify an existing design.

Specifically, it is known that both OSS and OSS's communities demonstrate a high level of modularity (Weber, 2004:59-65, 86-88) or granularity (Benkler, 2006:100-101) which is a structural property of distributed organizations. Modularity is highly connected with the feasibility of voluntary large scale parallel processing of a project. If CAD files with the supporting documentation constitute the main "source code" of OD, then the knowledge contained in CAD files should be organized and built in a modularized way. GNU/Linux, Wikipedia and other known commons could not have been developed to that magnitude if they were not synthesized as an assemblage (DeLanda, 2006: 25-31) of interconnected and semi-independent parts. But this is not the case of microhouse, as nowadays most design CAD platforms are shaped to fit a much different mode of production, ranging from the sole designer to medium-sized interdisciplinary teams. The first mode results to an unstructured aggregation of geometrical data, while the second to a closed and hierarchically relational organization of preset entities known as Building Information Modelling. The uploaded design CAD files of microhouse belong to the former data organizational structure while both are totally inadequate for CBPP. Even the imposed organization of tools, technologies and types could not be characterized as a modular knowledge structure. Tools being a mallet and a stepup unit are totally independent from the rest categories. Technologies are either nested inside types as in the case of WREN or added-on in the case of OWL but neither is articulated in a modular way in order to synthesize types.

Furthermore, especially in the case of microhouse, more than in the other cases, in order to support a DGML practice, the shared types have to be easily adjustable according to local or individual needs. It is oversimplistic to consider as realistic case, the widespread application of OSH standard housing types all over the world, regardless how many the number of types are. Consequently, it is required to incorporate type differentiation parameters in type design that will make easier the engagement of the community and the application of each type to different site, climate and materials among others. At this point, it seems less arduous to produce parametric housing types that are more easily adapted to local conditions than creating a new type for almost each one instance. In other words, OD and the design global imperative refer to a potentially globally customizable design, rather than to a worldwide shared conventional design. In the former case is required to design the change instead of the actual object's properties. The global gestion leads on to a relational or procedural object definition rather than a finished and unique artifact. It could not be overlooked that Wikipedia entries as well as OSS modules are defined in relation to other entries or modules resembling a distributed network organization. Equally the inner structure of an OSS module is procedural or in other words algorithmic as it is designed to face in steps a range of cases rather than one only case. OD could not be limited to the merely shared and editable design but it should also incorporate the design that is structurally open to change. On the other hand, the conventional architectural design toolset could not support the aforementioned workflow. To summarize modularity is analysed both as a parameter affecting collaboration as well as a method of discrete differentiation.

WREN and OWL technologies score 6/8 (Table 2) as besides non-editable assembly instructions they lack licence allowing commercial reuse. Microhouse is released under CC BY-SA 3.0 while WREN system under the copyleft MPL 2.0. Despite fundamentally disagreeing with rating commercial reusability as an openness parameter, it is important to stress that actually WREN system as well as systems's licence is nested into Microhouse type. In the case of nested modules of common knowledge which share different licences it remains vague how this criterion is evaluated especially if considered that the use of likert-type scales in open-o-meter is explicitly non preferable (Bonvoisin et al., 2017: 5). Even it may be possible to fork repository and alter microhouse type design, it is practically impossible to produce fabrication drawings without utilizing WREN solver. Taking into consideration the distinction between design and fabrication CAD files as highlighted in the case of Opendesk, WREN could be characterized as the explicit cognitive process going from design to fabrication files.

Furthermore, what is interesting at both type and technologies designs is that they have been accomplished and released under a proprietary and commercial design platform. It is generally accepted that OSS design platforms are not so common and have not approached yet the functionality of commercial platforms possibly with the exception of Blender (Velkova, 2016) which is addressed to visualization rather than design industry. Nonetheless, this is a highly restrictive fact regarding contribution potential, as it automatically excludes a great amount of the community. Moreover, it should be noted that this is not part of open-o-meter evaluation but it certainly and severely affects the ability of a project to be characterized as open. To reformulate open-o-meter criteria regarding CAD files, they need not only to be in native file format but in open file format as well.

In spite of what type and technologies have in common they have a fundamental difference. WREN system is not designed in conventional CAD platforms as in the case of microhouse development but it is created in visual programming environment (Figure 4) which functions as an extension of a conventional and proprietary CAD platform. Visual programming as well as classic programming (scripting) seems to be in-line with a relational or procedural definition of the design. Concequently, CAD files are not necessarily the only design files which was an axiomatic admission for open-o-meter framework.

AN EMERGING OD DIRECTION

Open-o-meter has a double function in the field of the OSH. On the one hand, it is a tool for the quantitative assessment of practices' openness. On the other hand, it serves as an OSH programmatic definition, a kind of guide for startup open projects. Despite the fact that open-o-meter remains the only systematic openness' evaluation framework, it has been proven to have certain limitations, highlighted by the examined case studies. Furthermore, some of the case studies examined in this paper reveal an inverse dynamic. While they intentionally keep certain parts of design development as totally closed procedures, ultimately they do not manage to achieve actual openness to parts that they keep wide open. Additionally, even the most open practices failed to demonstrate OSS and CBPP structural features. As a result, most practices prefer to be self-defined as open in an open-washing spirit rather than being actually open. Generally, the more substantial limitations faced by tools and practices refer to the classic problem of what is the "source code" of OSH. The most interesting realization is that WREN system as a model may be a hopeful answer to this question.

Tool and practices limitations

Specifically, the open-o-meter tool could be optimized according to a further specification or interpretation of the OSH principles (study, make, modify, distribute). What are actually required to achieve those four degrees of freedom are the following: open "source code", open contribution and open license, restricting any private or commercial appropriation. Even if those sound oversimplistic, we should always take into account that the source code of the OSH and the OSS potentially have more in common than differences as both are completely immaterial digital commons. Hardware's open source property could be described in detail to the following points:

- Design and fabrication files, as well as the congnitive process going from one to the other should be openly shared in the native format. It is almost pointless to provide only design files and omit fabrication files and the intermediary process or in any other combination. It would be like sharing one half of the source code of software. All three parts act in a complex synergy in order someone to be able to study, make and modify.
- Design platform whether the design is processed in conventional CAD, visual programming or classic programming, it has to be open and produced as well as maintained in the commons framework. An openly shared design for studying, making and modifying that was produced in a native proprietary format is a dead-end in itself. The issue of proprietary platforms at the framework of netarchical capitalism was extensively described by Kostakis and Bauwens (2014b: 23-29). We acknowledge the fact that open CAD platforms are scarce. This is partially attributed to the premature phase of the OSH in general, as well as to the nature and history of the - architectural - design itself. The latter will be analyzed furtherly below at practices limitation paragraph. In any case, it is relatively arguable to believe that OD platforms scarcity is subject to change in the near future.
- Supporting data such as BOM, assembly manual or any other technical documentation in editable format is required but it is in no case of equal importance to the previous set or to open contribution. Especially in small scale projects this kind of documentation may be painlessly omitted. Open-o-meter should integrate a system of scaled evaluation depending on the gravity of each criterion in order not be imprecise.

The prerequisite conditions for open contribution that are related to the advancement of open-o-meter methodology are the following:

- Hardware's "source code" ought to be modular in the same way that OSS and Wikipedia are. Especially in large scale hardware projects such as Wikihouse or other it is of critical importance to build digital design commons in a modular way. Big chunks of "source code" are practically precluding contribution and peer production. To a smaller extent, they affect even the ability to study a design. Though it is clear that "source code" modularity should be included to the evaluation criteria, it is neither clear nor simple how it could be acheived. It is a property that can be defined and measured quantitatively according to network science methodological tools (Newman, 2010: 231-220) but examination's ease or difficulty is highly dependent to the form of digital design commons. Definitely, geometrical modularity is not sufficient or necessary condition to produce a modular data structure. In any case, the research on potential forms of modularity in OD and their relative impact is a virgin territory that could be specified in the future.
- An open and unconditionally accessible collaboration platform should be considered a required infrastructure, for the evaluation of an OD community with reference to OSS standards. In most OSS cases collaboration platform also serves as sharing platform and repository. Digital commons are backed by communities build up beyond spatial limitations and synchronous collaboration restriction. Any mature OD community should exceed the boundaries of the founding members and in that sense, collaboration and sharing platform is indispensable. It is self-evident that sharing and collaboration platforms should not be proprietary (Kostakis and Bauwens, 2014b: 23-29).

To conclude, regarding tool limitations it has been shown by the current research an obvious relation between for-profit organizations and lower levels of openness. In this sense, we strongly believe that open license requirements should conform to FSF standards. Moreover, license requirements should refer to all nested modules of "source code".

Regarding the examined practices' limitations, apart from any minor detail or inconsistency, the greater common deficiency is the intentional or not lack of open and collaborative project developement. If this fact seems self-explained to the for-profit projects, it certainly needs further elaboration to the others. It should be noted that the OSH scape is generally characterized as premature comparing to OSS scape not only due to the recent history of the former, but also due to the inverse trajectories between software design and hardware design. Software development gets started as free and open source from the very beginning. Generally prior to 1980s software was a "free" and open source complement of hardware before shifting to an autonomous bussiness (Shirky, 2008:240; Bessen, 2002). On the other hand, what we expect from the development of OSH communities nowadays is exactly the opposite. We expect them to turn a fully commercially and intellectually appropriated enclosed field, to an open source peer production scape. To strengthen the argument, this trajectory is far longer for hardware being neither electronic nor mechanical as it is mostly based on an artisanal design approach far from design destined for mass production. For instance, the modus operandi of architectural design is historically founded on a 1:1 analogy between design and artifact, upon which are based the notions of the unique prototype, the sole author and the central absolute control over artifact properties.

CAD vs Digital (Parametric – Algorithmic) Design Commons

OSS and OD apart from the inverse trajectories, they share a more important structural difference. It is illustrated by the distance between source code and drawing. The basic axiomatic assumption of open-o-meter is that CAD files - along with documentation - are the hardware's "source code". CAD represents the computerized rather than the actually computational (Terzidis, 2006: 57-58) conventional - architectural - drafting toolset, including representations of orthogonal projections (plan, elevation, section drawings) and/or 3d models. The structural collaborative deficiencies faced by all examined projects, lead to the following question. Is it feasible to constitute a corpus of digital commons from conventional CAD files? The drawings of many well-known buildings are easily available on the web but does this actually means that they are individual examples of OD principles? Certainly following Conway's law (Conway, 1968), it can be logically deducted that design commons could not be an aggregation of conventional design elements and methodologies, as initially suggested by early advocates of OD (Vallance et al., 2001). In an analogy, OSS theorists have already described the structural differences between open source and proprietary developed code (Osterloh and Rota, 2007, Baldwin and Clark, 2006, Raymond 1999b,). In any case, the software code or a Wikipedia entry is an explicit form of knowledge, while the drawing is a representation (arrangement of lines) of an object that does not reveal the actual design knowledge that contains. In other words, we can trace a relation between what is considered as hardware's "source code" and the limited impact of some of the most prominent OSH projects in this field. In a similar controversy between the parallelization of collaborative writing and scripting code, Shirky (2005: 488) notes:

> *"Instead of assuming that Open Source methods are broadly applicable to the rest of the world, we can instead assume that that they are narrowly applicable, but so valuable that it is worth transforming other kinds of work, in order to take advantage of the tools and techniques pioneered here."*

During the last decade many architectural schools have integrated code learning to their curriculum (Papalexopoulos, 2011: 5), going from a computerized analog drafting method to a computational workflow. Additionally, many individually produced design code snippets have been uploaded to proprietary platforms' repositories [12] due to the aforementioned lack of OD platforms. Even the little known controversy at 2011 [13][14] between the creator of the freely distributed plugin named Kangaroo and the geometry rationalization company Evolute GmbH, is apocalyptic of the shift of interest from the drawing to the code. In this sense, WREN system seed may exemplify the future development of OD in the OSH framework. WREN system as already analysed is a development in visual programming environment, which covers a specific part or more accurately procedure of a greater design scheme (Wikihouse), being at the same time as generic as required to be useful for other design schemes also. Actually, WREN system concentrates the properties of what Papalexopoulos (2011) characterizes as Digital Design Commons:

> *"Digital Design Commons are pools of a multitude of micro- architecture problem solutions, a multitude of micro - syntaxes covering partial aspects of design, waiting to be actualized in larger design schemes.*
> *They also deny the unique and ultimate "form" in favor of a network's syntax. They tend to substitute the object's design with the design of networked multiplicities. Finally, they question the ubiquity of design as an end of work process, linking it to the (local) use value production."*

Digital Design Commons as instantiated by the WREN system are characterized by:

- Interoperability or external modularity. The practice of coding involves the decomposition of a complex problem into smaller and simpler pieces. This strategy makes feasible the re-use of generic knowledge modules to other problems instead of starting each time from a tabula rasa as in the case of conventional design approaches.
- Internal modularity. OSS in general is modular (Baldwin and Clark, 2006). This makes considerably easier to study or more importantly to modify in large scale collaboration network every single bit of knowledge.
- Abstraction or parametricity. Code in its nature is not dimensionally specific but rather generic. Consequently code is not a finished object but a process producing a stochastic multitude of objects able to be instantiated according to local inputs. This seems as an adequate answer to two hard questions. Why should we use digital fabrication means to manufacture locally indentical objects? If user innovation (Von Hippel, 2005:33-43) emerges at the dichotomy between mass production and heterogenous needs how could we utilize digital fabrication potential (differential manufacturing) without designing each one object separately?

CONCLUSION

The aforementioned OSH analysis shows that both the theoretical framework (open-o-meter) and the specific practice scape (Opendesk, Openstructures and Wikihouse) are premature, comparing to the the reference of OSS. The OSH's theoretical background is constrained to a great extent on the one hand by the OSS programmatic principles and manifestoes and to the other hand by the typical design's cognitive background and workflow.

Whereas OSS principles and definitions form a necessary theoretical starting point, there are intrinsic and contextual differences related with the material nature of OSH that should have been taken into account. For instance, digital fabrication as illustrated by differential and distributed manufacturing should have been reflected to a comprehensive definition of OD, as integral part of OSH. Additionally, open-o-meter is biased by the preconception that OSH is the hardware with publicly accessible design or in other words that OD is the publicly shared conventional design. In contrast, it is known from OSS experience (Raymond, 1999b) that open source code is structurally different from corporative developed source code. Consequently, open-o-meter fails to map effectively the actual "source code" in the examined subset (neither electronic nor mechanical) of hardware.

Furthermore, open-o-meter builds an OSH conceptual framework, complying with OSS programmatic input principles, while it omits to check inversely whether OSH-compatible projects output features compatible with OSS's generic structural properties such as modularity (Osterloh and Rota, 2007, Baldwin and Clark, 2006). As a result, highly open hardware projects according to open-o-meter such as Wikihouse fail to be modular and collaborative in the same way that most well known OSS programs or digital commons are. As theoretical background and practices are bidirectionally correlated most of the open-o-meter limitations refer to the practices as well. Computational design or design through visual programming as illustrated by Wikihouse component may be a hopeful answer to current limitations. Future research is needed in order to provide a consistent and comprehensive OSH conceptual framework according to the suggested directions.

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ENDNOTES

[1]https://opensourcedesign.cc/wiki/index.php/Open-O-meter, last visit: 01/07/2018
[2]https://www.tapr.org/TAPR_Open_Hardware_License_v1.0.pdf, last visit: 01/07/2018
[3]https://en.wikipedia.org/wiki/List_of_open-source_hardware_projects, last visit: 01/07/2018
[4]https://xtools.wmflabs.org/articleinfo/en.wikipedia.org/List_of_open-source_hardware_projects
The "List of open-source hardware projects" is a dynamic entry first edited in 2010, featuring 683 edits by 328 editors at the time of writing, most of them characterized as major edits. Last visit: 01/07/2018
[5]https://wikihouse.cc/, last visit: 01/07/2018
[6]https://www.opendesk.cc/, last visit: 01/07/2018
[7]http://openstructures.net/, last visit: 01/07/2018
[8]http://beta.openstructures.net/pages/2, last visit: 01/07/2018
[9]https://en.wikipedia.org/wiki/WikiHouse, last visit: 01/07/2018

[10]https://github.com/wikihouseproject/, last visit: 01/07/2018
[11]https://github.com/wikihouseproject/Microhouse/, last visit: 01/07/2018
[12] https://www.food4rhino.com/, last visit: 01/07/2018.
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FIGURES

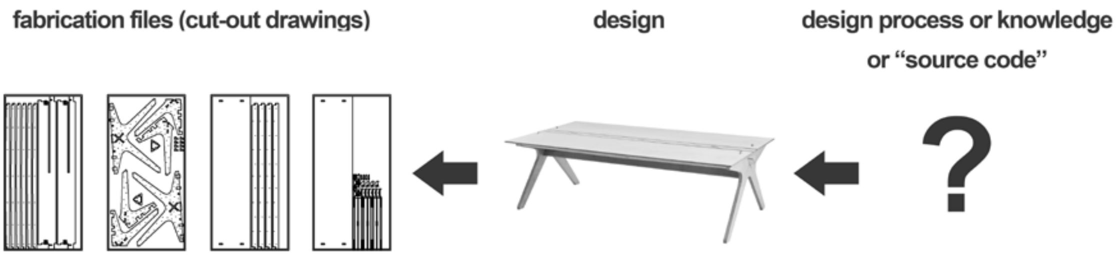

Figure 1. Opendesk shared CAD files in relation to the design "source code".
(image processing: author, image source: https://www.opendesk.cc/, last visit: 01/07/2018)

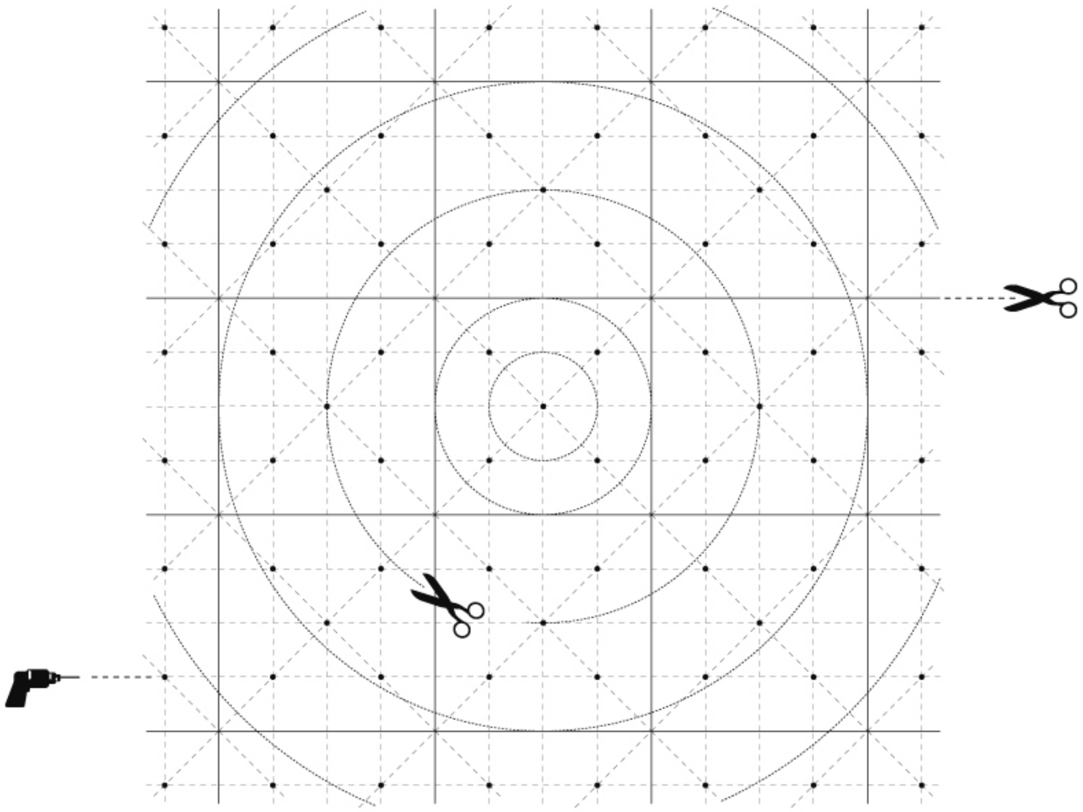

Figure 2. OpenStructures modular grid
(source: http://beta.openstructures.net/block_images/0000/0242/grid4.jpg?1268343038, last visit: 01/07/2018)

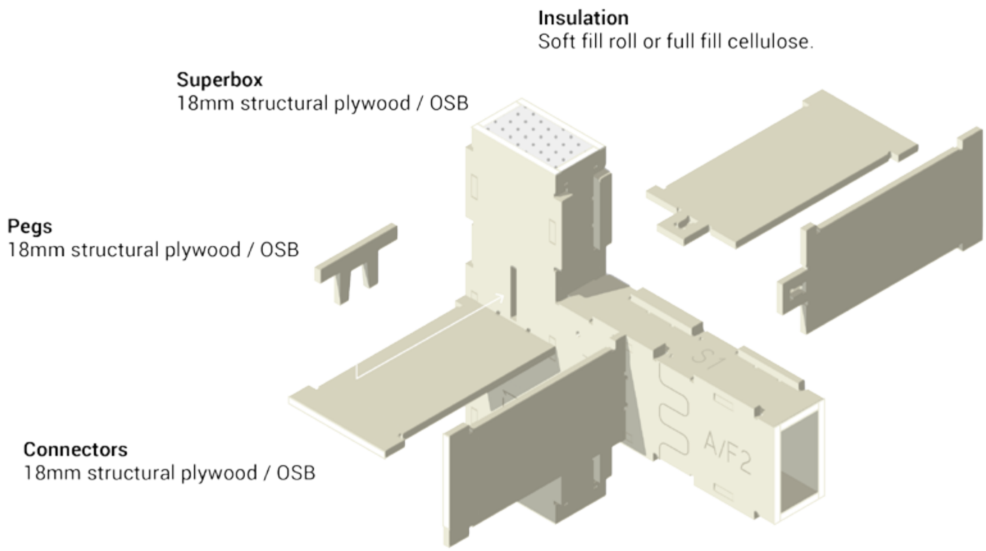

Figure 3. WREN system (source: https://github.com/wikihouseproject/Wren/raw/master/Images/Connectors-01.png, last visit: 01/07/2018)

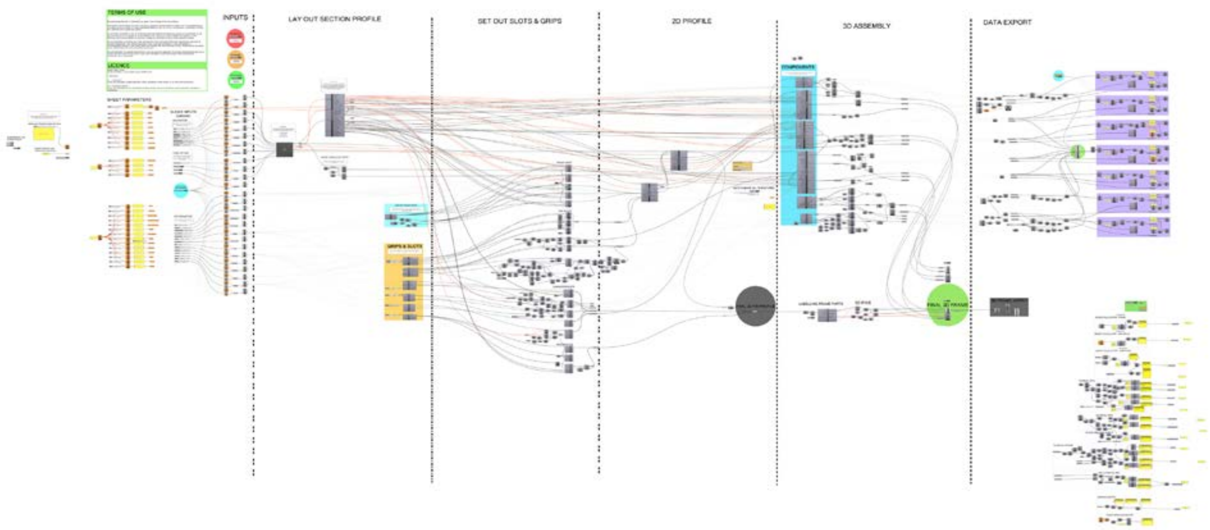

Figure 4. WREN system's source code in visual programming environment (source: https://github.com/wikihouseproject/Wren/blob/master/WikiHouse_WREN_(v4.3).gh, last visit: 01/07/2018)

APPENDIX

OPEN-O-METER (Bonvoisin et al., 2017)		
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.

Table 1. Open-o-meter. OSH product characterization criteria (Bonvoisin et al.,2017)

OSHWA Principles 1.0	study	make		modify				distribute	
Balka et al. (2014)	transparency	replicability		accessibility					
OPEN-O-METER (Bonvoisin et al., 2017)	CAD files available	assembly instructions a vailable	bill of materials available	CAD files editable	assembly instructions e ditable	bill of materials editable	guidelines for participation	commercial usage allowed	**SUM**
WIKIHOUSE MICROHOUSE (TYPE)	1	1	1	1	0	1	1	1	**7**
WIKIHOUSE WREN SYSTEM (TECHNOLOGY)	1	1	1	1	0	1	1	0	**6**
WIKIHOUSE OWL INTERNAL DOOR KIT (TECHNOLOGY)	1	1	1	1	0	1	1	0	**6**
OPENDESK	1	1	1	1	0	0	0	0,5	**4,5**
OPEN STRUCTURES	0,5	0	0	0,5	0	0	1	0,5	**2,5**

Table 2. Openness evaluation