IDENTIFYING THE FACTORS AFFECTING THE REPLICABILITY OF OPEN SOURCE HARDWARE DESIGNS

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ABSTRACT

Open-source hardware (OSH) development is a new design paradigm from a commercial perspective. Openly sharing designs of technical products is a step towards democratising access to new technologies for the benefit of individuals and communities in society. At the core of the open-source hardware definition lies the freedom for anyone to replicate the hardware based on the design. Thus, enabling this freedom is a step towards developing a successful OSH. Previous research supposes that a bill of materials and assembly instructions are enough for this. In this study, we question this assumption and investigate what other factors may influence replicability of an OSH. Using data from a survey and interviews with OSH practitioners, we identify and describe these factors, which relate to the documentation, the design and the context of the person replicating the hardware. Using these insights, we present a diagram of the replication process along with questions the person replicating the hardware would ask to check whether an OSH is replicable. Finally, we synthesise this information into practical advice for OSH projects to increase the replicability of the designs they produce, and thus the likelihood of their project's success.

Keywords: Open source design, Open source hardware, Open innovation, Design practice, Design reuse

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1 INTRODUCTION

Open-source hardware (OSH) development is a new design paradigm from a commercial perspective. Openly sharing the designs of technical products is a step towards democratising access to new technologies for the benefit of individuals and communities in society. Open source as a development and intellectual property management mode has reached substantial success in the software sector, and may be as impactful in product design and development of hardware in the future. Research in OSH development studies amongst other things: 'openness' levels of projects (Balka, 2011; Bonvoisin *et al.*, 2018; Bonvoisin, Mies, *et al.*, 2017; Yanamandram and Panchal, 2014); business models (Pearce, 2017); product development process organisation (Bonvoisin, Thomas, *et al.*, 2017); community roles, behaviour and modes of participation (Boujut *et al.*, 2019; Li *et al.*, 2019) and motivations (Hausberg and Spaeth, 2020; Li *et al.*, 2017). One of the topics for engineering design research is to look at how end users use the design output from OSH development projects. OSH projects can have two types of end users: those who buy a pre-assembled hardware or a self-assembly kit, and those who build the hardware artefact themselves from scratch, sourcing, modifying and manufacturing all the individual components and finally assembling them, using the technical design output produced within the project. We define this process as 'replication'. After replicating the hardware, they may be: using it themselves; sharing it within a community setting; customising or modifying it, therefore creating a variant; or even selling the product as a finished item. If the maker is choosing to sell the product, then additional considerations such as safety issues and warranties would be of concern, but we do not address this in this preliminary study into OSH replicability.

Replicability, i.e. the ability of a person or persons (builder(s)) to build a functioning version of the hardware in their location is of paramount importance to OSH, since it is at the core of the OSH definition (Open Source Hardware Association, 2018). It is one of its unique characteristics compared to proprietary hardware (i.e. most conventional products on the market), whose designers and manufacturers tend to want to *prevent* people from replicating their designs. As such, OSH licenses and relevant standards (*DIN SPEC 3105-1:2020-09, Open Source Hardware - Part 1: Requirements for technical documentation*; Bonvoisin et al. 2020) address the ability to replicate the OSH as a freedom which should be fostered by OSH projects. However, a licence allowing a person to make (i.e. replicate) the hardware, does not necessarily enable the freedom to make it. In other words, while they are allowed to make it, it does mean they *can* make it. A variety of factors play a role when it comes to what is needed in order to allow a person to be able to make a piece of hardware, namely information, materials and equipment. While open-source software (OSS) literature is relevant, we cannot assume that replicability is the same in OSH. Replicability in open-source software is different than OSH, as it involves reading and running software code, whereas in the world of hardware there is the element of replicating physical objects, which introduces a new set of variables and considerations, such as materials and manufacturing. Our literature review showed little to no research into replicability in OSH. Consequently, there is a lack of practical advice for increasing OSH replicability for projects.

In this paper, we focus on this topic of replicability and explore more precisely what factors affect replicability, and how an OSH project might take these aspects into consideration and act accordingly in order to improve the replicability of their hardware. This not only helps them comply with the OSH definition and relevant standards but would also help them gain more users who build the hardware themselves, something which project teams define as a metric of success - based on one of our studies. Replicability relates to getting more end users/builders, which benefits the project. They could build on the knowledge and develop new versions of the hardware which effectively is a type of design iteration, enabling the design to improve further. As OSH development is ultimately a particularly challenging scenario in which to design robust, reliable and reproducible hardware, learnings from this paper could also contribute new ideas to more conventional technical engineering design situations, such as proprietary industrial product development.

2 LITERATURE REVIEW

A manual online search of specific conference proceedings and journal papers since 2010 with the keyword **replicability** and its synonyms including **reproducibility** and **repeatability** shows that those terms are ambiguous and their interpretation depends on the community the research belongs to (Barba, 2018; National Academies of Sciences, Engineering, 2019; Plesser, 2018).

In the field of computer science, Rougier et al. (2017) define reproducibility as "*running the same software on the same input data and obtaining the same results*", and repeatability as "*writing and then running new software based on the description of a computational model or method provided in the original publication, and obtaining results that are similar enough*". The Association of Computing Machinery (ACM), which concentrates on computational experiments, suggests sound definitions relying upon two concepts: the team and the experimental setup ("Artifact Review and Badging - Current", n.d.). According to the ACM, repeatability involves the same team and the same experimental setup, this means that a researcher can reliably repeat their own computation. Replicability involves a different team and the same experimental setup, this means that an independent group can obtain the same result using the author's own artefacts. Reproducibility involves a different team and different experimental setup, this means that an independent group can obtain the same result using artefacts which they develop completely independently.
Similarly, we could establish some parallels with our research topic, that is, OSH development, by substituting the team with the community and the experimental setup with the source. In our universe of discourse, a community is the set of makers actively involved in a web-based OSH project. Note that a community is sometimes limited to a single maker, especially at the beginning of the project. The source is all the media required to satisfy the four degrees of freedoms of OSH: to study, to modify, to make, and to distribute.
Repeatability (*Same community, same source*.) The requirements of the hardware can be satisfied with stated tolerance by the same community using the same verification procedure, under the same operating conditions on multiple trials. For OSH design, this means that a community can reliably repeat their own hardware.
Replicability (*Different community, same source*.) The requirements of the hardware can be satisfied with stated tolerance by a different community using the same verification procedure, under the same operating conditions on multiple trials. For product design, this means that an independent community can obtain the same[1] hardware using the original community's source.
Reproducibility (*Different community, different source*.) The requirements of the hardware can be satisfied with stated tolerance by a different community using the same verification procedure, under the same operating conditions on multiple trials. For product design, this means that an independent community can obtain the same[1] hardware result using source that they develop completely independently.
When searching in academic databases such as Web of Science, Scopus or Google Scholar, we observe that, in our communities of interest including product design, design science, and engineering design, the term "product replicability" does not occur very often: 16 results from 2010 in Google Scholar. When expanding queries to related terms, we notice that product replicability should not be confused with product remanufacturing (Matsumoto *et al*., 2016) or product reuse (Galbreth *et al*., 2013) that consist in an industrial process that turns used products into products with same requirements as new products - i.e. restored to "as new" condition. Moreover, the term "design reuse", that is, the reuse of successful designs in part or in whole for a new design (Sivaloganathan and Shahin, 1999), might appear as a synonym to "product replicability". However, reuse can lead to a different product though design changes, whereas replicability aims at making the same product from the original design source. Therefore, to the extent of our knowledge, product replicability has received little, if any, attention in research for industry.

Research aim

Nevertheless, with the recent development of OSH, the need for replicability was briefly discussed (Bonvoisin, Mies, *et al*., 2017). In this study, the authors state that replicability of a design is a necessary condition for prototyping and production, which in turn defines a design as being 'open source', addressing the freedom to make an OSH. In addition, they claim that an OSH is replicable if its documentation contains the assembly instructions and the bill of materials. However, our background in design and manufacturing encourages us to ask the research question: **are the assembly instructions and the bill of materials the only necessary conditions to replicate an OSH?**

[1] More or less some deviations that belong to the intervals of tolerance prescribed by the requirements.

While this could be, in some cases, true, in this study we suggest that these two documentation artefacts, while being important, are not sufficient to replicate an OSH. Thus, we propose the following hypothesis, which we address using data from interviews and a survey with OSH practitioners: **the assembly instructions and the bill of materials are necessary but not sufficient conditions to replicate an OSH.**

In this paper, we will identify the factors influencing OSH replicability, presenting them in a replicability process, and outlining the process which an individual may go through when evaluating whether an OSH is replicable for them. Based on this, we make suggestions regarding good practices which OSH projects can employ, to improve the replicability of the OSH they develop.

3 RESEARCH APPROACH

To understand replicability and what factors influence it, we draw upon insights generated from a survey and interviews with OSH practitioners. We then summarise that information in a diagram depicting the process an individual would follow to replicate an OSH artefact.

Survey of OSH practitioners

A survey was carried out to gather opinions of OSH practitioners on what constitutes success in OSH development projects. Three open questions were asked, to elicit responses on success factors, success metrics and best practices for success in these projects. The survey was conducted in paper format at an event focusing on OSH development, as well as in online format where it was disseminated on the social media platform Twitter.

Thirty responses were received, with the majority given by OSH practitioners, and 4 given by people who have an understanding of OSH and have an intention to participate or publish their own designs as OSH. Ten of the responses were in physical format and twenty were online. The responses were analysed through open coding and alluded to a number of elements that characterise successful OSH projects.

The survey responses were segmented and analysed into different themes, which were then grouped into categories. One of the main conclusions was that a successful OSH is one that is replicable by people other than the originator(s), with 12 responses explicitly highlighting replicability as a success factor for OSH. Delving deeper into this replicability aspect, we collected all the references in the survey responses which related to this directly or contained information about what could influence it. Out of the thirty responses received for the survey, sixteen of them included references that related directly or indirectly to replicability of OSH and what factors influence it.

Using all this information relating to replicability and synthesising it together with knowledge from the literature, we develop a flowchart to demonstrate the process of verifying whether an OSH is replicable by a person external to the project. It highlights all the salient considerations that the person has to take into account in order to decide whether it is possible for them to replicate that OSH.

Interviews of OSH practitioners

Fifteen interviews were organized with OSH project founders and makers. The interview guide was designed in order to understand the practitioners’ approaches to design reuse and was articulated in 3 sections. The first general section aimed at capturing the motivations, the preferences in terms of tools, artefacts and contents search when engaged in a reuse activity. The second section focused more on the motivations to share with communities the result of their design and a third section focused on motivations to engage in sharing activities with companies. The interviews lasted from about 30 to 50 minutes.

Qualitative content analysis was used to analyse the data. The interpretation and classification were done by three reviewers in an iterative process. This methodology leads to an interpretation of the contextual meaning of specific terms or content (Haidar et al., 2019). Each segment was verified by three researchers and the interpretation was discussed during review sessions.

Step 1: The interviews were transcribed and segmented. Only design reuse statements were considered. These statements can refer to needs, problems, practices, tools, etc. At this step no distinction was made, but 'solutions' were tagged with an S and other statements were tagged with an N. Each statement has been tagged with a number (Ni, Si). A total of 176 segments were identified.

Step 2: Each of the selected statement contents was interpreted and synthesized. This gave some pre-concepts (themes). That were aggregated into higher level concepts for the findings.

Step 3: A matrix was constructed from step 2, where the synthesized statements were translated into needs formulations. This matrix served as a basis for the elicitation of the influencing factors presented table 1.
Since, in this paper, replicability is not fully synonymous with design reuse, we elicited and analysed only the aspects related to replicability and identify the main influencing factors. This is presented in section 4.

4 FACTORS INFLUENCING OSH REPLICABILITY

In this section we summarize the influencing factors we elicited from our survey and interviews. These factors cover the various aspects of the replication process and will serve as a basis for the definition of an ideal process for supporting replicability of OSH. We have identified four main categories of influencing factors, which are displayed in Table 1.

Table 1. Factors influencing the replicability of OSH

Category	Factor	Description	Interviewed projects and survey responses
Quality	Documentation standardisation	Documentation structure, format following documentation guidelines and templates. Complexity of the documentation (adapted to product complexity).	Recyclebot, Farm Hack, Recyclebot, Echofab, 1 survey participant
	Documentation dynamics	Documentation relates to the latest developments and version of OSH. External persons are able to participate in the documentation elaboration and modification process.	Farm Hack, Recyclebot, Appropedia, Wikispeed, 2 survey participants
	Documentation accuracy	Documentation is clear and ensures a sufficient rigor and correctness of the contents that allows the rebuilding of the product.	Farm Hack, Tympan, Echofab, Magnetic resonance imaging, OKF
	File formats	File formats used allow replication on standard and easily accessible machines. Use of readable open-source formats.	Echofab, Magnetic resonance imaging, Wikispeed, 5 survey participants
	Design rules	Presence of design rules that facilitate replicability, for example taking into account fabricability and procurement of parts.	Magnetic resonance imaging, Wikispeed, 2 survey participants
Completeness	Documentation of design rationale	Key points to consider are documented, such as risks of failure and troubleshooting.	Farm Hack, Tympan, Appropedia, Wikispeed, 3 survey participants
	Documentation of design content	Is enough information communicated through the documentation to enable someone to build a working version of the OSH?	NimbRo, 12 survey participants

Table 1. Factors influencing the replicability of OSH (continued)

Category	Factor	Description	Interviewed projects and survey responses
Accessibility	Accessibility of the project	How easy is it to find the OSH project? Is the OSH and the associated project popular?	Farm Hack, Magnetic resonance imaging, OKF, Wikispeed, 16 survey participants
	Accessibility of documentation	Is the documentation published in a public repository/webpage where it can be accessed freely? Is it available in multiple languages?	5 survey participants
	Availability of materials and equipment	Are the required materials and equipment available to the builder?	5 survey participants
	Metadata and search	Metadata for facilitating the search and retrieval of existing designs, documentation and associated authors. How easy is it to find the documentation? How easy is it to view?	Farm Hack, Echofab, Magnetic resonance imaging, Appropedia, Wikispeed, 1 survey participant
Ease of manufacture and assembly	Knowledge and skills	How easy is it for a person to build the hardware? What level of skills, materials, tooling, and processes are needed?	OKF, 1 survey participant

First, *accessibility* is a factor that influences the ability of a maker to find the proper documentation associated with the design. Therefore, when the searched element is found, the maker should have access to the documentation through the same web-based platform as the original design. Linked to accessibility, the ability to have a relevant search function is then of prime importance. The ability to find information by using search keywords is an important factor for accessibility. Additionally, accessibility should be understood as the ability to access the required manufacturing facilities or tools. Hence, accessibility is twofold: accessibility of the documentation (finding/searching) and accessibility of the manufacturing equipment and materials.

Second, when the documentation is found, its *completeness* influences replicability. Completeness is understood as the amount of information required to replicate the product. This includes manufacturing information, materials information and assembly instructions. However, sometimes the information embedded inside the documents does not allow the correct replication. Some of our interviewees raised the fact that troubleshooting and errors are worth being mentioned so that one does not fall into the same traps when replicating the hardware. Explanation on the rationale of some decisions may shed some light and avoid mistakes in the fabrication. We refer to this as *design rationale*.

Third, the *quality* of the hardware design and its documentation appears as a key factor category. This is the one that has been the most mentioned in our interviews and survey. Quality of documentation increases with good standardization of the documentation. Not surprisingly, the quality is linked to the completeness, rigor and accuracy of the documentation, which are complementary factors. Another factor is the dynamics of the documentation. Living documentation, evolving with the hardware versions and feedback of the users, is also likely to be more useful and increase replicability. As one fundamental characteristic of OSH is participation, allowing end-users to engage in commenting and modifying the documentation is also a way to gain participants. The builder thus becomes a contributor. The quality of the design itself is also an influencing factor as good rules to make the design easily replicable, taking into account manufacturing materials, etc. was also a quality factor for our interviewees.

Finally, the *ease of manufacture and assembly* is an important factor category as it results from the previous factors. This category contains the factor knowledge and skills, which refers to the capacity of the documentation to convey enough information so that the maker can build enough knowledge in order to successfully replicate the piece of hardware. The capacity to anticipate the skills and know-how necessary to avoid traps will reduce the learning curve of the maker and avoid numerous trials and errors. The next section will explore how these factors can be connected to a typical replication process and how they can help to make suggestions to improve replicability.

5 OSH REPLICABILITY PROCESS

The diagram in Figure 1 displays the process of replicating an OSH (squares), including the checks (diamonds) an individual would do when establishing whether the OSH is replicable or not (rectangles).

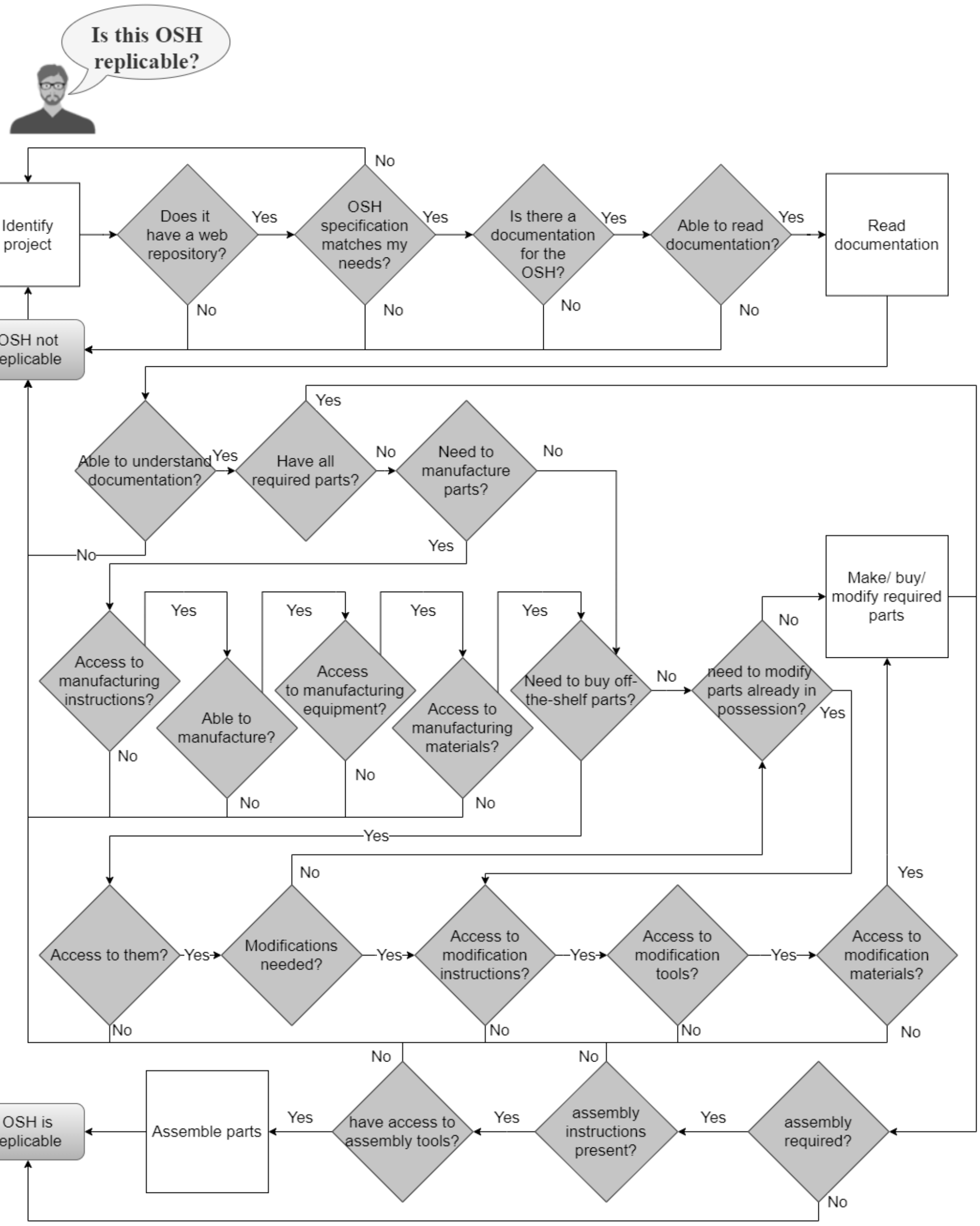

Figure 1: The process of determining whether an OSH is replicable

6 SUGGESTIONS TO IMPROVE REPLICABILITY OF OSH

The factors which affect OSH replicability can be split into two categories: the ones that the project can influence, and the ones it cannot. The former includes the documentation content and formats shared, as well as the design rules used to design the OSH. The latter involves the knowledge, skills and context of the OSH builder. While the project cannot control the latter, it can certainly take it into consideration for generating design and documentation rules. Table 2 presents suggestions for practices a project can employ to improve the replicability of the OSH. These practices originate either directly from the survey and interview participant responses, or through synthesis by the researchers based on that information.

Table 2: Suggested practices for increasing replicability of OSH

Suggestion overview	**Suggested practices**	**Replicability factors addressed**
Use design for manufacturing and design for assembly good practice	Consider global availability of materials, parts and equipment, particularly at location of target audience	Availability of materials and equipment
	Select materials, parts and equipment widely available to general public, particularly target audience	
	Minimise number of materials, parts and equipment	Ease of manufacture and assembly
	Minimise number of manufacturing tasks	
	Minimise complexity of manufacturing	
	Minimise complexity of assembly e.g. use as few connections and fixtures as possible	
Ensure documentation includes all the information needed to build the most recent version of the OSH	Publish BoM	Documentation of design content
	Publish all manufacturing files (e.g. CAD drawings, 3D printing files) needed to make bespoke parts	
	Publish text and/or audio-visual instructions for manufacturing bespoke parts (if required)	
	Publish text and/or audio-visual instructions for modifying existing parts (if required)	
	Publish text/audio-visual instructions for assembly	
	Continually update the documentation keeping it up-to-date and accurate. Allow people to add feedback and comments	Documentation dynamics; documentation accuracy
Ensure documentation is readable	Use open source file formats	Documentation file formats
	Use formats readable with standard software	
Ensure documentation is easy to understand	Use clear, easy-to-understand language, avoiding jargon	Documentation standardisation
	If it is necessary to use jargon, explain terms and use glossary when appropriate	
	Structure the documentation systematically	
	Avoid unnecessarily complex documentation	
Ensure the documentation is accessible	Publish documentation with an open source license	Accessibility of documentation
	Publish documentation in public project repository/ website	Accessibility of documentation; metadata and search
	Place documentation in easy-to-find location	
	Have clear and obvious names for documentation files	
	Have a documentation index	
Communicate the design rationale and other salient information	Publish risk of failure and troubleshooting information	Documentation of design rationale
	Describe the minimum skills required for manufacture and assembly of the OSH in the documentation	Knowledge and skills
Provide additional support	Publish FAQ	Knowledge and skills
	Provide support to builders about the replication process e.g. have a forum/email for answering build-related questions	

7 CONCLUSIONS

Open source hardware development is gaining increasing popularity in the recent years, and its impact on product design and development may be substantial but is yet to be confirmed. The results we present here are a first step towards understanding what influences OSH replicability based on a survey and interviews of OSH practitioners. Our findings verify that the bill of materials and assembly instructions are important for replicability, in partial agreement with (Bonvoisin, Mies, *et al.*, 2017). However, we also propose a number of other factors influencing replicability, asserting that the mere presence of a bill of materials and assembly instructions does not, by itself, confirm replicability. Thus, the original hypothesis for this study is verified. The factors which influence replicability relate to the documentation contents, structure and formats, as well as the physical requirements for building the hardware (materials, equipment, practical skills, etc.). We have drawn upon this information to make suggestions for practices which OSH projects could employ to improve the replicability, and thus the success of the OSH they develop. Future work could include empirical studies focusing on replicability from the specific perspective of the 'builders'. Furthermore, specific studies for different application contexts could be conducted, e.g. for commercial hardware which would involve safety and warranty considerations. An additional aim for future work would be to identify evaluation metrics for communities to build indicators of replicability in order increase the reach and impact of their designs.

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