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Characterising Open Source Hardware Development: Insights into Project Success, Project Types and Hardware Replicability
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Characterising Open Source Hardware Development: Insights into Project Success, Project Types and Hardware Replicability

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Declaration of any previous submission of the work

The material presented here for examination for the award of a higher degree by research has not been incorporated into a submission for another degree.

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Declaration of authorship

I am the author of this thesis, and the work described therein was carried out by myself personally, with the exception of "Defining Success in Open Source Hardware Development Projects: A Survey of Practitioners" where roughly 15% of the work was carried out by other researchers, and "Identifying the Factors Affecting the Replicability of Open Source Hardware Designs", where roughly 40% of the work was carried out by other researchers.

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Dedication

To my mum and dad: I dedicate this work to you, whose love and support know no bounds. The opportunities arising in my path were carved out by your continual sacrifices.

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List of abbreviations

IP	Intellectual property
OSH	Open source hardware
OSHD	Open source hardware development
OSS	Open source software
NPD	New product development
OSHWA	Open Source Hardware Association

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Abstract

Open source development has been broadly studied within the context of software since the early 2000s, while this topic has only been broached in the context of hardware – i.e., physical products – in the last decade or so. In that time, open source as a mode of development of physical products – called Open Source Hardware Development (OSHD) – has become increasingly popular and has garnered scientific discourse. While numerous publications present new open source hardware (OSH) products and their designs, little literature shines the spotlight on what some OSH practitioners and academics call 'meta' aspects of OSHD – the product development processes, practices and methods used in OSHD projects. This research focuses upon studying OSHD as a phenomenon, with the aim of characterising it as a field by highlighting some nuances that differentiate it from other related fields (such as open source software development, and new product development project management).

In this nascent field, there are numerous possible avenues for research that emerge. In this thesis, the research questions explored relate to the breadth of the field: what success looks like in OSHD projects and whether there are any unique types of OSHD projects. Additionally, this thesis also addresses research questions that investigate the field in depth – specifically, the aspect of replicability in OSH, which is a core part of openness. In line with the research questions, this doctoral thesis aims to contribute to the knowledge in both theory and practice in the field of OSH through three studies:

1. An investigation into what characterises successful OSHD projects from the perspective of practitioners, with a comparison with open source software development and new product development literature
2. An inquiry into the breadth of variety of OSHD projects using a typological approach, identifying distinct project types
3. An investigation into OSH replicability through: shedding light on the replication process; identification of the factors affecting replicability; suggestions for practitioners about how to improve OSH replicability in their projects; and a discussion on whether the OSHD project types (from 2.) can help inform the applicability of the suggestions to different projects.

Through a qualitative survey with practitioners, three top-level characteristics of successful OSH projects were found: successful projects (1) create value to a number of stakeholders and in a number of ways; (2) create high-quality outputs; and (3) have effective processes. Under each of these top-level characteristics, further characteristics, practices and related metrics were identified which aid theoretical understanding as well as inform practice. Using a mixed-methods approach, three OSHD project types emerged: (1) hobbyist electronics projects (2) professional projects and (3) unfunded projects. Lastly, an investigation into a fundamental aspect of OSHD project success, hardware replicability, and what practices could help improve it is

presented along with a discussion of the potential for the three project types to inform the suggestions.

Overall, this thesis provides three studies which help characterise the field of OSH by drawing comparisons across OSHD and other related fields as well as comparisons within the OSHD field. It makes a first step into creating empirically-based best practice advice guidelines which are currently lacking in the field, and therefore helps to inform both theory and practice.

Section 1. Introduction

The central locus of this thesis is open source hardware development (OSHD), a phenomenon which takes a different approach to product development and intellectual property (IP) management, compared to traditional, closed source, new product development (NPD).

Researchers are interested in this topic because of its underpinning ideology and related practices, which are contrasting to that of conventional, closed source NPD. This interest has sparked research into topics such as: practitioner motivations; the meaning of openness (Balka 2011; Bonvoisin and Mies 2018); business (Pearce 2017; Thomas 2019); and project practices (Bonvoisin, Thomas, et al. 2017; Bonvoisin et al. 2021; Dai et al. 2020), to name a few. In this thesis, three studies are presented which together contribute towards further characterising the field of OSHD.

In this section, a high-level overview of the research phenomenon, OSHD, and its relevance in today's world is given in section 1.1. Then, section 1.2 delves deeper into core concepts and background literature, creating a foundation for the thesis. Section 1.3 outlines the research methodology of this thesis through a description of the research approach, research aim, research objectives, and research questions, as well as other sources of insight and inspiration. This section concludes with an overview and description of the structure of this thesis in section 1.4, which can serve as an aid for readers to refer to.

1.1 Introduction to the research phenomenon and its relevance

In this section, the phenomenon of OSHD is introduced, along with its relevance in today's world.

1.1.1 What is OSHD?

Open source hardware (OSH) 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 2018). Open source as a mode of development of physical products (i.e., OSHD) is becoming increasingly common in recent years (Ferdinand 2018). Under the umbrella term 'open source', both a product development methodology and a philosophical, ideological and socio-political approach to IP (Carillo and Okoli 2008) are encompassed. The origin of the concept of OSHD comes from the world of software, with open source software development (OSSD) being a mature field which has been researched in depth over the last two decades. By contrast, OSHD is a new field which researchers have started paying attention to in the last ten years or so.

Traditional NPD is usually focused on capturing value (i.e., profit (Bowman and Ambrosini 2000)) through secrecy and the so-called 'protecting' of IP through patents (James et al. 2013). Secrecy is by its nature in direct contrast to 'openness', the key feature and ethos of OSHD. Patents, on the other hand, do contain a certain element of 'openness' by the definition of the word in that they reveal the mechanism of operation of a product along with illustrations of its design. A key difference though lies in their main purpose: to prevent others from copying the design and from making, using or selling the product without the permission of the patent owner. The latter is also in contrast with the definition of OSH given by the Open Source Hardware Association (OSHWA) (2018). As such, OSHD is a radically different approach to product development and IP management, and it provides unprecedented opportunities as well as challenges within the field itself, but also in the wider field of product development.

1.1.2 OSHD as a new phenomenon

Von Krogh et al. (2012) define phenomena as "regularities that are unexpected, that challenge existing knowledge (including the extant theory) and that are relevant to scientific discourse" (pp. 278). One such phenomenon is OSHD. It is unexpected because it is a mode of development which focuses upon sharing hardware designs openly with the public – a stark contrast to the current norm of hardware NPD which focuses on the secrecy of designs and so-called 'protection' of IP through patents, in order to reduce market competition. It challenges existing knowledge because: (1) it presents an alternative opportunity for capturing value; (2) there are different ways of working and different IP management practices meaning that potentially challenge existing best practices; (3) it is a radically new way of developing physical products which has not yet thoroughly been studied in the literature. Finally, it is relevant to scientific discourse because it extends upon and participates in the recent scientific discourse on open source. This is in line with Von Krogh et al. (2012) who equate the growth of the significance of a phenomenon to the interest and attention it receives in the scholarly community. The timeliness of this topic can be further demonstrated by the fact that the number of OSHD projects has increased substantially in recent years.

1.1.3 The relevance of OSHD in today's world

The new phenomenon of OSHD is becoming increasingly popular, demonstrated both by the number of new OSHD projects as well as the number of research publications on the topic.

OSHWA has a database which lists OSHD projects which have self-certified to comply with their definition of OSH (more on this in section 3). By the end of May 2018, 180 projects were listed there (Bonvoisin and Mies 2018); on 24th March 2021, 1527 projects were listed (Antoniou et al. 2022); on 7th September 2021, 1663 projects were listed (Antoniou et al. 2022); and at the time of writing (26th August 2022) the researcher noted that 1865 projects were listed. This demonstrates that the number of OSHD projects (which are self-certifying as such) is increasing, as shown in Figure 1.

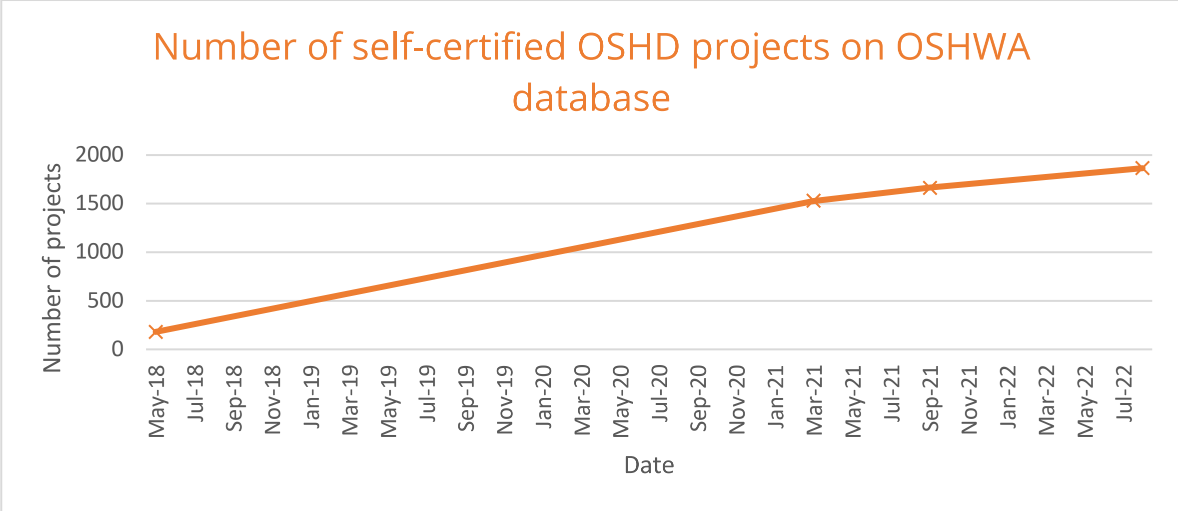

Figure 1: Number of self-certified OSH projects on the OSHWA database between the years 2018 and 2022.

Searching on Scopus[1] the term "open source hardware" (with quotation marks to ensure that the words appear consecutively) yields 1,023 results[2]. The cumulative number of publications in each year is shown in the graph in Figure 2. This graph shows a large increase in OSH-related publications over the last decade. This indicates an increase in the popularity of the OSHD phenomenon in research, demonstrating the timeliness of the research presented in this thesis.

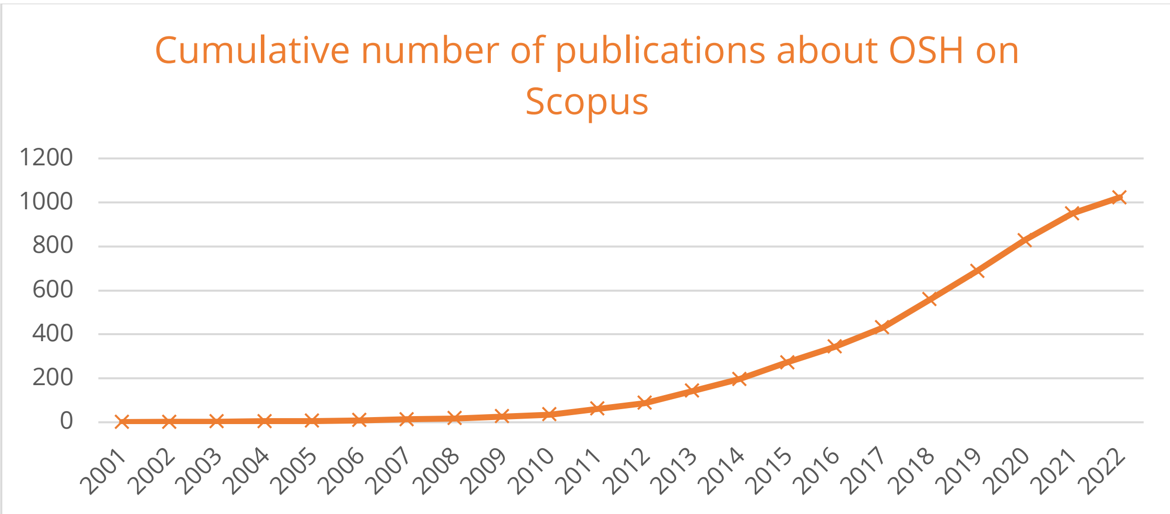

Figure 2: Cumulative number of publications on Scopus when searching "open source hardware" on 26th August 2022.

1.2 Foundational concepts and background literature

This section delves deeper into the topic of open source, giving some core background information and terminology used in the field and this thesis.

[1] https://www.scopus.com

[2] On 26th August 2022

1.2.1 What is open source?

When a product is open source, it means that its users have four freedoms: (1) to use it for any purpose, (2) to study it, (3) to make and redistribute copies of it, and (4) to make changes to it and share them (Stallman 2002) since its design (source) is openly accessible to the public, usually through licensing (*The Open Source Definition | Open Source Initiative* 2022). This means that open source can be thought of as an IP management archetype, due to the copyright implications it entails. After the coining of the term 'open source', it quickly became a movement (Cassel 2018), as like-minded people joined in.

The open source movement initially started with software, through a "radical retake of copyright law" (Carillo and Okoli 2008) to enable the public to develop and use software freely. OSSD in fact resembles the early days of software development. Much of the early software development took place in academia and corporations, whose research culture involved freely exchanging and building upon each other's software code (Von Hippel and Von Krogh 2003). Examples of well-known **open source software (OSS)** include Android (Snider et al. 2014), the Mozilla Firefox browser, and the Linux operating system (Mockus et al. 2002). OSS usually involves the collaboration and pooling of knowledge of companies, suppliers, customers and people with related skills to create a shared technology (Chesbrough et al. 2006). Over the years, OSS has enjoyed high popularity and has become commonplace (Snider et al. 2014). For example, Red Hat, a software company that provides OSS to businesses, was acquired by IBM for $32 billion (Volpi 2019). This is an example of how the rise of OSS has also led companies to re-evaluate their traditional business models which were heavily focused on IP (Volpi 2019).

This archetype which was established from OSS, and the associated open source ethos, opened the way to the more recent emergence of open source hardware (OSH) (Bonvoisin et al. 2018), where hardware refers to physical, tangible products. The main motivation and benefit is that OSH gives the public "freedom to control their technology while sharing knowledge and encouraging commerce through the open exchange of designs" (OSHWA 2018). The OSHWA (2018), in line with the Open Source Initiative definition (The Open Source Definition | Open Source Initiative n.d.), define OSH as "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". In the case of OSH, the 'source code' refers to the "schematics, blueprints, logic designs [and] CAD drawings" (What is open hardware? | Opensource.com n.d.). Open source hardware development (OSHD) tends to follow similar principles as OSSD, i.e., 'the open source way': a series of values and practices in open source communities; namely: transparency, collaboration, early and often releases, meritocracy, and community (Opensource.com n.d.). Both OSS and OSH have associated licences (for a list of example licenses see Licenses & Standards | Open Source Initiative (n.d.)).

1.2.2 The meaning of 'openness'

Project openness is an ill-defined concept. 'Openness', in everyday language, can be defined as "lack of restriction, accessibility" and "lack of concealment" (Lexico.com n.d.). A few researchers attempted to characterise openness in open source projects. For example, Raasch et al. (2009) identify two types of openness: product openness and process openness.

Product openness refers to how much design documentation (CAD files, bills of materials, etc.) of the final product is made freely available to the public. The two extrema of the spectrum of product openness are closed source hardware and OSH. The former are physical products for which documentation is not freely available to the public, while the latter are products for which design documentation is freely available to the public, usually with open source licencing (Bonvoisin et al. 2018).

Process openness addresses the 'intention' of assembling a group of voluntary participants to take part in the design process. In order to have process openness in a project, transparent product development processes which enable interested persons to get involved must be maintained (Bonvoisin et al. 2018). Product development projects lie within a spectrum of process openness, with projects with high process openness having product development processes open to external persons to get involved, while projects with very low process openness do not. Researchers such as Bonvoisin et al. (2018) call these 'open design' and 'closed design' projects. This terminology is further explored in section 1.2.3.

Raymond (2001), in his seminal book on OSSD, identifies two modes of development of OSS, which can be useful illustrations of product and process openness. These are described in Figure 3.

'The cathedral'
open product
closed process

- OSS developed by individuals or groups of individuals working in isolation
- "[software] built like cathedrals, carefully crafted by individual wizards or small bands of mages working in splendid isolation, with no beta to be released before its time".

'The bazaar'
open product
open process

- everyone is allowed and welcomed to participate
- "open to the point of promiscuity"
- "a great babbling bazaar of differing agendas and approaches out of which a coherent and stable system could seemingly emerge only by a succession of miracles"

Figure 3: The two modes of development of OSS according to Raymond (2001): 'the cathedral' and 'the bazaar'.

While a few researchers (such as: Bonvoisin and Mies 2018; Gavras 2018; Balka et al. 2014; Balka 2011; Yanamandram and Panchal 2014) discuss different characteristics that relate to openness, there has been no widely-accepted and empirically-proven assessment framework for defining project openness. A first attempt for an OSHD project openness assessment has been made by Bonvoisin and Mies (2018) through a framework termed 'Open-o-Meter'. The Open-o-Meter has eight openness criteria, five of which relate to product openness and three of which relate to process openness (Bonvoisin and Mies 2018). A scoring spectrum of 0-8 is formed using the criteria to measure the openness of an OSH project, with 0 being 'fully closed' and 8 being 'fully open' Figure 4 shows the Open-o-Meter criteria separated in terms of product and process openness.

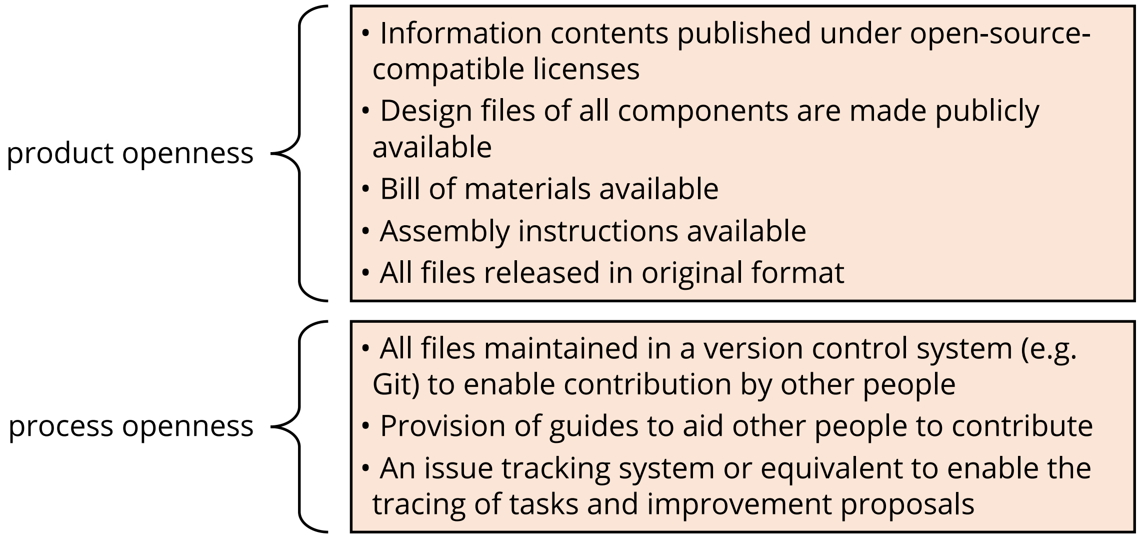

Figure 4: The eight Open-O-Meter criteria (adapted from (Bonvoisin and Mies 2018)

Bonvoisin and Mies (2018) pose that the presence of contribution guides, issue tracking systems and version control systems show how open the development process is. However, there are other factors which could demonstrate process openness that the authors did not include, such as usage of communication streams, usage of collaboration software, level of accessibility of project documentation, and level of adoption of external contributions. Therefore, it can be deduced that the process openness criteria they define are very few and not all-encompassing. It can also be concluded that while the Open-o-Meter provides a first step in defining and assessing openness, it shows only a limited view of how openness could manifest.

OSHD is a field that currently lacks standardisation. A few steps have been taken to make it more standardised, such as the widely accepted OSH definition and certification programme by OSHWA. More formal standards have started emerging, such as DIN SPEC 3105 (2020) and the Open Know-How Manifest Specification 1.0 (Wardeh 2022), but their adoption is yet to be determined. As such, it can be said that the concept of openness is multi-factorial and ill-defined, making it difficult at this point in time to establish clearly defined and enforceable criteria. However, the discussion on openness reported here suggests that the critical question is not *whether* a project is open, but *how open* it is.

1.2.3 Terminology

When exploring the literature on OSHD, readers are confronted with a variety of terminology and an apparent lack of consensus on the usage of terms. The literature uses a multitude of terms, such as 'open source hardware development', 'open design', 'open source hardware design', 'open innovation', 'open source innovation', 'open content' and 'open source product development'. This is perhaps a symptom of the field being still immature, without widely accepted common terminology. This section aims to define the different terms used and explicate the terminology which will be used in this thesis henceforth.

1.2.3.1 Disambiguation of terms

Open source hardware development (OSHD)

As stated in section 1.1.1, OSHWA (2018) defines OSH as "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". The term 'hardware', refers to physical artefacts. Katz (2012), one of the leading open source specialist lawyers, advises thinking of hardware on a spectrum of 'softness' to 'hardness' and mentions hardware could be anything from field programmable gate arrays (FPGAs) to stormtrooper helmets and even statues.

Open design and OSH design

Open design is a term often used in the literature. It has been found to have divergent meanings, as different researchers have different and even conflicting definitions for it (Bonvoisin et al. 2018), leading to confusion. Vallance et al. (2001) attempt to give the first open design definition, after noticing confusion between similar terms. They created what was to be a living document with the definition, which is unfortunately no longer a living document at present.

Open design and OSH design are terms which are often used to refer to the same phenomenon as OSHD (see, for example, Raasch et al., 2009). The literature does not explicate a distinction between the two. However, confusion may arise when open design is used as a noun to describe a *process* versus a noun to describe an *artefact.* To illustrate this point, the 'Open Design Manifesto' uses the latter, and refers to an open design being "[computer aided design] information published online under a Creative Commons license to be downloaded, produced, copied and modified" and "produced directly from file by CNC machines and without special tooling" (Kadushin 2010).

This definition created by Kadushin (2010) seems to be referring only to the outcome of the design process, i.e., the product, not the design process itself. This seems to be referring to what OSHWA (2018) refers to as OSH. Fjeldsted et al. (2012) suggest that open design is synonymous with what they call 'open source development', which refers to the development of both OSS as well as 'tangible products' i.e. hardware. Boisseau et al. (2017) define open design as follows:

> *"The state of a design project where both the process and the sources of its output are accessible and (re)usable, by anyone and for any purpose".*

The two latter works are referring to open design as an *open process*, whereas Kadushin's (2010) requirements refer only to the *open outcome*.

Open innovation or open source innovation

Chesbrough (2003) states that in the last few decades, industry experienced a change in how companies "commercialise industrial knowledge". He observed a shift from the 'closed innovation' paradigm to that of 'open innovation'. The closed innovation paradigm involves a focus on innovation *control* (heavy focus on IP) and firm *self-reliance* (the notion of: "to create successful products we need to develop them ourselves"). This paradigm has worked exceptionally well for a while, but several factors, namely companies no longer being 'knowledge monopolies', began eroding closed innovation leading to more open innovation. Chesbrough defines this as the use of inflows of knowledge to enable faster innovation internally, as well as the outflows to broaden the markets for the external use of innovation.

Balka (2011) defines open source innovation as the "free revealing of information on a new design with the intention of collaborative development of a single design or a limited number of related designs for market or non-market exploitation". A clear aspect of this definition is that there has to be an intention for participants to collaborate, whereas in OSHD there may or may not be an intention for collaboration. Open innovation and open source innovation appear to be used interchangeably. Additionally, some authors employ a wider interpretation of the term and include both OSSD and OSHD under the umbrella term open source innovation. For example, Huizingh (2011) adopts the point of view that open source can be thought of as a subtype of open innovation.

Open content

Open content is a term that refers to non-physical and non-software matter (Balka 2011) such as Wikipedia articles[4], online recipes, and geographic maps such as OpenStreetMap[5].

Open source product development

The term 'open source product development' is sometimes used in different ways in the literature. Balka (2011), for example, appears to use this term to encapsulate the development of both tangible objects and 'information goods'. Bonvoisin et al., (2018)

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[4] https://en.wikipedia.org/
[5] https://www.openstreetmap.org

describe open source product development as community-based product development and define it as: "the development of complex OSH products performed in a collective process allowing the participation of any interested person." Zhou and Zhang (2018) similarly assume collaborative development in the usage of the term open source product development.

Bonvoisin et al. (2017) note that open source product development projects have the following five aspects:

- A platform: a meeting place for contributors
- A drive: a motivation for the contribution
- A community: the team of contributors
- A development 23efine23.
- A business model

Here, beyond collaborative development, having a business model is also added to the definition of open source product development.

1.2.3.2 Terminology used in this thesis

In this thesis, the preferred terminology for the topic at hand is OSH and OSHD. When using the term OSHD, this thesis refers to the product design and development process of developing OSH. In this sense, OSH is to OSHD as a closed source product is to closed source NPD. Literature which refers to 'open design' or 'OSH design' (as a process, not an artefact), is sometimes referring to this same topic, and other times to the development of an OSH using an open process.

OSH as a term has a widely accepted definition by OSHWA (2018) which is frequently used in the field and appears broad enough to capture different types of physical products. This thesis uses this definition of OSH and refers to OSHD as the process by which OSH is developed. Furthermore, the terms OSH projects and OSHD projects are used interchangeably, to refer to projects which develop an OSH. Additionally, this thesis adopts a broad point of view of what could constitute as hardware, similar to Katz, (2012).

The term open design is not used because it can be confusing, as it can describe both an artefact and a process. It also appears limiting because one definition assumes CNC production without specialist tooling (Kadushin 2010), while another assumes a fully open process (Boisseau et al. 2017). Open source innovation is not used either because it again has multiple interpretations in the literature. Balka's (2011) usage of the term imposes collaborative development, which may or may not be present in OSHD. This thesis aims to explore the development of OSH in more general terms and does not intend to impose the restriction of having collaborative product development. In fact, one of the studies presented explores the presence (or lack of) collaboration in OSHD projects (section 3). The definition of open source product development by Bonvoisin et al., (2018) also assumes collaborative development, having only complex products and in other studies it also assumes having a business model (Bonvoisin, Thomas, et al.

2017). The study performed by Bonvoisin et al. (2018), confirmed that OSHD fills a continuum between an open and closed process, and contradicts the view that open source is intrinsically community-based. The limitations of process openness, product complexity and presence of business models are not imposed on the projects studied in this thesis.

1.3 Research methodology

The previous sections described the OSHD phenomenon and an overview of salient literature. Key definitions and terminology were explained and the relevance of OSHD in the world was highlighted. This section presents the research approach for studying this emerging topic which is employed in this thesis, along with the research aim, research objectives, research questions and other sources of insight.

1.3.1 Research approach

Von Krogh et al. (2012) identify three phases of growth in the scientific study of a phenomenon: embryonic, growth, and mature. OSHD could be seen as belonging somewhere in between the embryonic and growth phase. It could be considered embryonic because of two reasons. One, OSHD is mostly studied by isolated researchers who do not belong to research groups, as few, if any research groups can be found focusing on OSHD. Two, research efforts in this field are often uncoordinated and often duplicated, which is indicative of the embryonic phase (Gilbert 1977). The OSHD phenomenon could also be considered to be in the growth phase because the number of publications in this field is continually increasing (see Figure 2), and because a small group of scholars is starting to aggregate and seems to be in the early stages of formation of a scientific community, demonstrated by the creation of the Open Hardware Research Network[6] in 2022.

For the reasons previously described, the field cannot be described as mature. Other researchers have also observed this, for example, Bonvoisin et al. (2021) describe the OSHD field as 'striving to gain momentum and maturity'. It is, however, desirable to increase the maturity of the field, because by doing so not only can knowledge gaps be closed, but also practitioners of the field can be helped through the creation of research-based best practices. Ultimately, this could help lead to more successful OSHD projects. This is important for the individuals participating in those projects, but also for the individuals benefitting from those projects, i.e., the users of the hardware. Lastly and perhaps most importantly, this is also beneficial to society, because the nature of openness in OSHD contributes to more access to information and technology for all citizens of the world.

Research with a focus on identifying and reporting on new or recent phenomena of interest to scientific inquiry, such as OSHD, is referred to as phenomenon-based research (von Krogh et al. 2012). It is important because in new phenomena it is difficult to generate theory without first observing and exploring its different aspects through

[6] https://open-hardware.network/

exploratory work (von Krogh et al. 2012)., which generates data and research strategies which then help inform subsequent studies (Simonson et al. 2001). In this thesis, exploration and observation are used to characterise the field of OSHD. Additionally, Simonson et al. (2001) pose that a goal of research should be to gain a better understanding of particular substantive phenomena, further supporting the importance of such an approach. Phenomenon-based research is also valuable because it can help bridge disciplinary divides by connecting a variety of scholars around a shared interest in the phenomenon (von Krogh et al. 2012), which in the case of OSHD is apparent through the fact that the literature originates from researchers from disciplines such as: mechanical and electrical engineering; management and organisational science; and social sciences, to name a few.

Von Krogh et al. (2012) argue that in phenomenon-based research, the following research strategies need to take place: (1) distinguish, (2) explore, (3) design, (4) theorise and (5) synthesise. Each of these strategies helps progressively increase the maturity of a field. The first, distinguish, involves distinguishing the key features of the field. The second, explore, involves delving deeper with new frameworks, observations and measures. The third, design, involves experimenting with new research designs. The fourth, theorise, involves the building of theoretical models, while the fifth and final strategy, synthesise, involves critically integrating and building upon previous theories and empirical studies.

At the time of writing, the literature landscape involves studies which adopt the first two strategies, with few studies, if any at all, experimenting with research designs, working towards developing theory and synthesising knowledge. This further indicates that the field of OSHD is in the 'growing' phase and not fully mature (Vos 2015; von Krogh et al. 2012). This immaturity is further demonstrated by the lack of consistency in the terminology used in the literature, as shown in section 1.2.3. In this thesis, the first three research strategies described by Von Krogh et al. (2012) are adopted.

Lastly, the research approach in this thesis takes the perspective that OSHD results in net good towards society. This is because it involves free offering of knowledge to individuals, without imposing secrecy or any legal repercussions for expanding upon or copying work of another. However, OSHD is not without its flaws. Take, for example, harmful devices such as 3D-printable guns. Today, there are a number of designs of such harmful OSH. This thesis takes the stance that harmful OSH such as guns form the minority of OSH that exist, and that the fact that certain individuals choose to create harmful objects as OSH is a problem that is not necessairy caused by the OSHD phenomenon itself.

1.3.2 Research gap, overarching research aim, research objectives, and research questions

In this section, the overarching research aim which was formulated as a response to the research gap is presented (section 1.3.2.1). Next, the research objectives which address the research aim, and more granularly, the research questions which correspond to each research objective are described (section 1.3.2.2). Figure 5 shows a diagram providing an at-a-glance view of the research gap, research aim, research objectives and research questions.

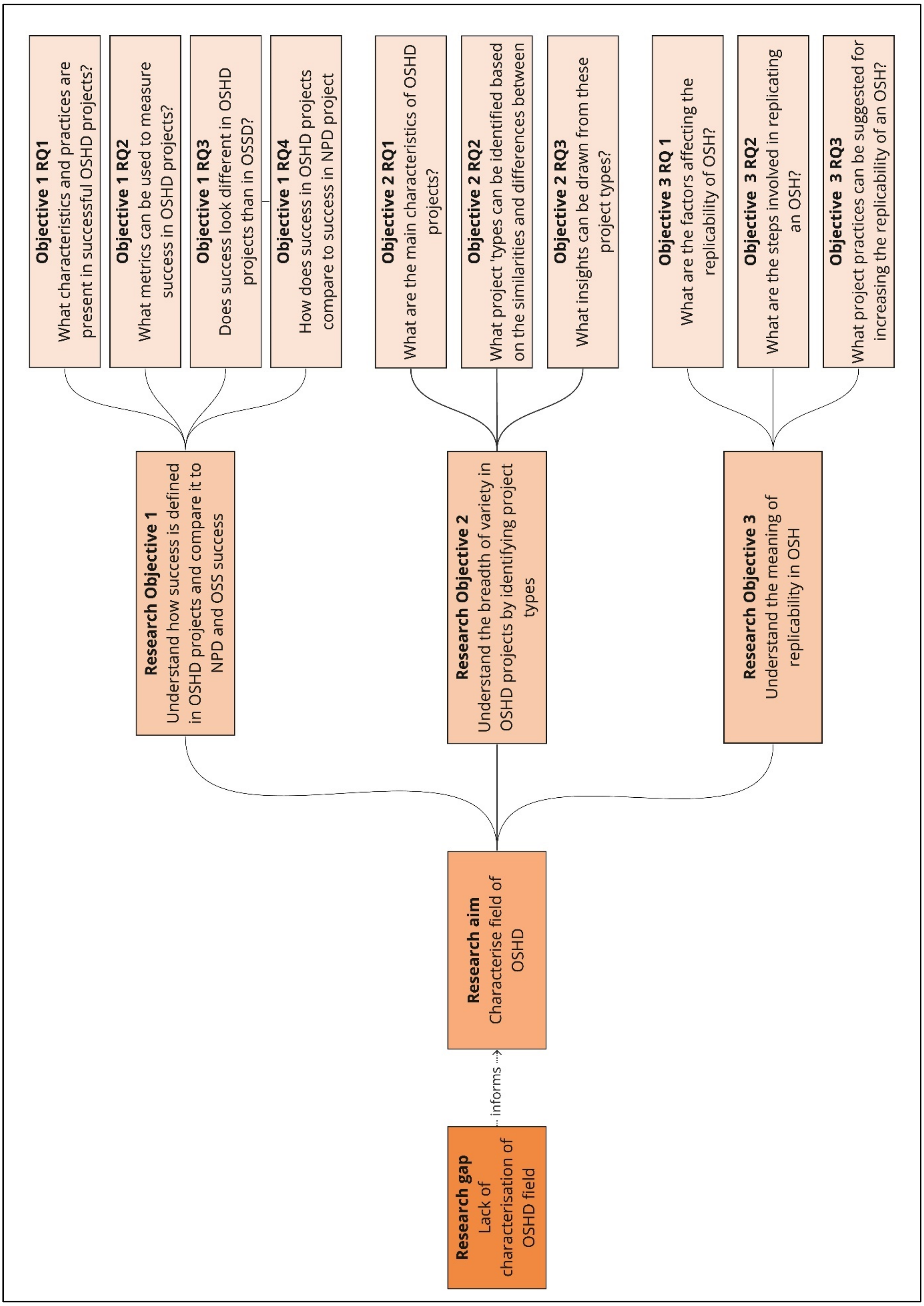

Figure 5: An overview of the research gap, research aim, research objectives and research questions (RQs) and their relationships.

1.3.2.1 Research gap and overarching research aim

Upon reviewing the literature in this field, it was observed that a major gap is the lack of characterisation of the field, which would help increase its maturity by contributing towards theory development. This includes both within the field (comparison of OSHD projects with each other) and outside the field (comparison of OSHD projects with other types of projects). Therefore, characterising the field of OSHD constitutes the overarching aim of this thesis.

Characterising a field is important for several reasons. First, characterising a field can help with understanding the scope and boundaries of the field, and differentiate it from related fields. By characterizing a field, researchers and practitioners can identify the main topics, themes, and issues that are relevant to the field. Secondly, characterising a field can help identify new gaps and opportunities for research. This can inform the development of new research questions, hypotheses, and methods. Additionally, doing so can also help to facilitate communication and collaboration among researchers and practitioners who work in the field. By having a shared understanding of the key concepts, terminology, and issues, researchers and practitioners can more easily engage in productive dialogue and collaboration. As shown in Section 1.2.3, there is inconsistent use of terminology and an overall lack of commonly accepted terms, and characterisation of the field could help with improving this. Furthermore, characterising a field can help researchers and practitioners establish a baseline against which to evaluate progress. This can help to identify areas of improvement and areas where further research is needed. Last but not least, characterising the field can help researchers and practitioners promote the field to the broader public and stakeholders, highlighting its importance and potential impact on society.

In summary, characterising a field provides a comprehensive understanding of the field and its development, which can help to inform research and practice. It also helps to identify gaps, opportunities and potential areas for future research. This overarching aim is addressed through three research objectives, which in turn, are fulfilled by one study each. These three studies help to characterise the field of OSHD by comparing it with other adjacent fields, comparing projects within the field, and tackling a core aspect of openness which has unique complexity in OSHD in particular.

1.3.2.2 Research objectives and research questions

This section details the research objectives and associated research questions addressed within each of the three studies presented in this thesis.

1.3.2.2.1 Study 1: OSHD project success

It was observed that research on the topic of project success was lacking, again indicating a still immature field. This is in contrast to the very mature field of NPD, for which literature on success, best practices and key performance indicators is abundant. Study 1 serves as a first step in understanding project success in OSHD projects and is presented in Section 2.

Success, in its traditional definition in common language, relates to the accomplishment of goals. Success criteria are important in any project, as they give its participants a focus for their efforts (Yu et al. 2005). Success criteria can help OSH practitioners "build effective forms of collective action and self-organisation" and "effectively create and capture value" (Troxler 2013). They can also aid in the formation of "a consistent identity and a set of commonly-accepted best practices" to help the OSH phenomenon become more mature (Bonvoisin et al. 2020). This is because employing best practices can help steer a project towards success (Griffin 1997). No significant attempts have been made to investigate what project success looks like in this specific mode of NPD.

To summarise, despite its relevance, there is a lack of comprehensive understanding of how success is defined in OSH projects, which has the potential to benefit both research and practice and can help inform best practice advice. Understanding success through the perspective of practitioners also helps uncover their drivers for doing OSHD projects. It also helps towards characterising the field of OSH by comparing and contrasting with similar fields such as NPD and OSSD. This leads to the first research objective:

Objective 1: Understand how success is defined in OSHD projects and compare it to NPD and OSS success

This objective is then broken down into four research questions (RQs):

Objective 1 RQ1 What characteristics and practices are present in successful OSHD projects?

Objective 1 RQ2 What metrics can be used to measure success in OSHD projects?

Objective 1 RQ3 Does success look different in OSHD projects than in OSSD?

Objective 1 RQ4 How does success in OSHD projects compare to success in NPD project management?

Objective 1 and its corresponding RQs are addressed in section 2. This objective was fulfilled by employing a qualitative approach to investigate practitioners' perceptions of OSHD project success using a survey questionnaire. Thematic analysis was used to analyse the data. The work presented in section 2 was published in the journal *Design Science* in the thematic collection titled "Open Design and Open Source Hardware Products" and is subsequently referred to in this thesis as paper A (Antoniou et al. 2022).

1.3.2.2.2 Study 2: Typology of OSHD projects

To contribute towards the maturity of the field of OSH, we must also understand the variance of projects within this field. Beyond some anecdotal descriptions, no research work was found that attempts to categorise different OSHD projects based on their characteristics. Such research is fundamental to characterising the field because it can help us understand the unique features of the field and would contribute as a first step towards theory development by comparing OSHD projects with each other. In the future, this could also contribute to understanding what practices could lead to different project types, as well as what practices are most relevant and helpful to each project type. Additionally, understanding the differences and similarities of projects could help scientific research by providing a framework which can be employed at different points in time in order to observe the evolution of OSHD projects and thus the field. By understanding the breadth of OSHD projects, we could take steps to offer specific best practice advice to those projects and their unique contexts and make progress towards understanding the causal effects between practices and outcomes. As such both practice and theory can be informed (Shenhar and Dvir 1996). The above can be summarised in the second research objective:

Objective 2: Understand the breadth of variety in OSHD projects by identifying project types

This objective is addressed in Study 2, presented in Section 3 of this thesis. Study 2 fulfils this objective by addressing the following RQs:

Objective 2 RQ1 What are the main characteristics of OSHD projects?

Objective 2 RQ2 What project 'types' can be identified based on the similarities and differences between the characteristics?

Objective 2 RQ3 What insights can be drawn from these project types?

Section 4 presents a study addressing objective 2 and its respective RQs using a mixed-methods approach employing a combination of qualitative and quantitative analysis.

1.3.2.2.3 Study 3: Replicability in OSHD projects

A core aspect of open source projects, both software and hardware, is replicability. In software, this is rather straightforward: one can deploy the code on their local machine (provided they have the necessary software requirements) and they can replicate the software product. In hardware, this is much more complex. While some authors (e.g., (Bonvoisin, Mies, Boujut, et al. 2017) assume that a bill of materials and assembly instructions constitute sufficient information to successfully replicate a hardware, the researcher hypothesised that there are more factors which influence the replicability of an OSH. This is a fundamental aspect of characterising the field because replicability is at the heart of open source. It is a key aspect of the field, and therefore, understanding replicability means understanding what it means to be open source in the world of hardware. Furthermore, understanding the factors contributing to replicability enables the possibility to develop best practice advice towards increasing replicability and as such increasing openness. This leads to the third research objective:

Objective 3: Understand the meaning of replicability in OSH

This objective is broken down into the following three RQs:

Objective 3 RQ 1 What are the factors affecting the replicability of OSH?

Objective 3 RQ 2 What are the steps involved in replicating an OSH?

Objective 3 RQ 3 What project practices can be suggested for increasing the replicability of an OSH?

Section 4 presents study 3 which explores possible factors affecting the replicability of OSH, founded upon the hypothesis that the bill of materials and assembly instructions are not the only ones, contrary to Bonvoisin, Mies, et al. (2017). Study 3 goes a step further and recommends some practices for increasing the replicability of OSH targeted towards OSHD project practitioners. It involves combining data sets collected and analysed through qualitative methods. This study was published in the proceedings of the International Conference On Engineering Design 2021 (ICED21) and won the reviewer's favourite award (Antoniou et al. 2021). Note that Objective 3 and its corresponding RQs are not explicitly stated within the main body of the published paper itself, but are implicitly addressed.

1.3.3 Other sources of insight and inspiration

This section introduces the Design Research Methodology and the OPENNEXT project, which provided additional sources of insights.

1.3.3.1 The Design Research Methodology (DRM)

Design research encompasses research which aims towards the development of understanding and the development of support for the field of product design and development (Blessing and Chakrabarti 2009). Design research is an overwhelmingly complex field in which a variety of methods from a variety of disciplines are required, which are often unfamiliar to design researchers (Blessing and Chakrabarti 2009). To navigate this complexity, the researcher drew inspiration for this research project from a methodology aptly named **Design Research Methodology (DRM)**, developed by Blessing and Chakrabarti (2009).

The DRM framework consists of four stages: research clarification, descriptive study I, prescriptive study, and descriptive study II. Each stage has certain outcomes and means of achieving them: the first stage, research clarification, involves identifying research goals through literature analysis; the second stage, descriptive study I, develops understanding through empirical data analysis; the third stage, prescriptive study, generates support through assumptions, experience and synthesis, while the final stage, descriptive study II, evaluates that support through empirical data analysis.

An outline of this is shown in the diagram in Figure 6. It is important to note that stages can also involve iterations (note the dark multiple-headed arrows in Figure 6).

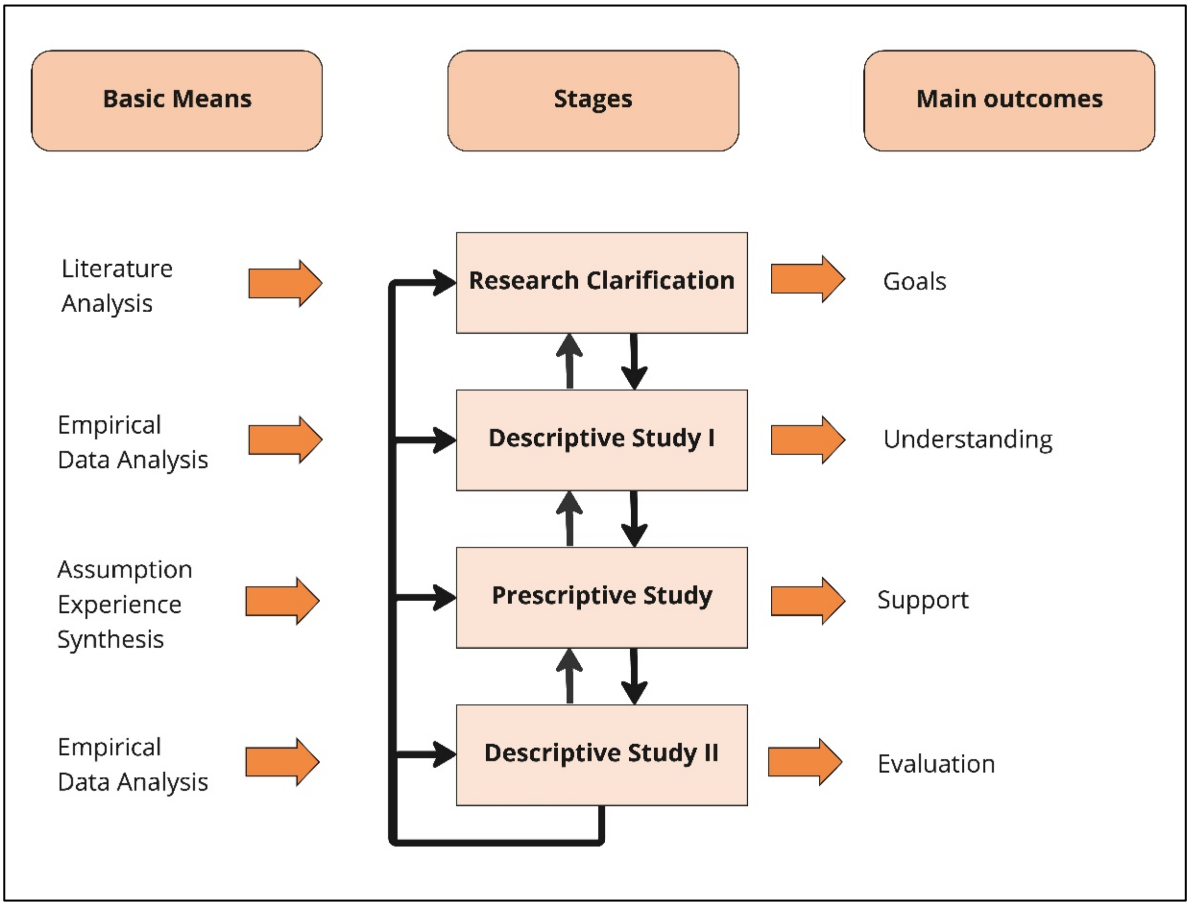

Figure 6: The DRM framework (adapted from: Blessing and Chakrabarti, 2009)

Blessing and Chakrabarti (2009) then propose six different types of design research projects, which involve combinations of the different stages. Research clarification and descriptive study I are present in all types and are thus essential. The research clarification stage involves literature review and the "[formulation of] a realistic and worthwhile research goal" (Blessing and Chakrabarti, 2009). Descriptive study I involves further literature review and relevant observational and analytical research to obtain a deep understanding of the current situation in the research phenomenon under study. The prescriptive study stage involves the employment of an intervention which would improve the state of the research phenomenon through the use of the understanding obtained in the previous two stages. Descriptive study II then involves the evaluation of the intervention concerning its ability to "realise the desired situation" (Blessing and Chakrabarti, 2009).

In the case of the research project presented in this thesis, review-based research clarification was carried out, as per DRM. Studies 1 and 2 could be seen as fitting the 'descriptive study I' description, as they involve a literature review and relevant observational and analytical research. Study 3 can be seen as both a descriptive study I and an initial prescriptive study because it includes a literature review, involves observational and analytical research, as well as some recommendations for potential interventions for achieving a 'desired situation' (i.e., increasing replicability of OSH projects) through synthesis. It is important to note, that study 3 does not apply any interventions but instead makes some recommendations which could be used for future interventions. This thesis does not include an evaluation of an intervention (i.e., descriptive study II). An approach focusing mostly on descriptive study I and an initial prescriptive study is well-suited to research topics which are new and do not have a lot of relevant literature, therefore requiring comprehensive descriptive studies rather than literature review-based ones, with more studies focusing on interventions and their evaluations (Blessing and Chakrabarti 2009).

1.3.3.2 The OPENNEXT project

Between 1st October 2020 and 31st August 2022, the researcher was employed as a Research Assistant in the international and interdisciplinary European Union-funded research project OPENNEXT[7]. This project brought together researchers, companies and fablabs/makerspaces with a common goal of "changing the future of product creation". More specifically, the collaborators in this project worked together towards a better understanding of OSHD and helped provide tools and resources to practitioners.

The researcher was involved in this project mainly by being an associate editor and project manager of the development of a handbook targeted towards companies looking to do an OSHD project. The researcher was involved in this endeavour from early on, starting from generating ideas for the book and leading up to managing a team of authors who wrote content for the book, reviewing content and overseeing timely delivery.

This project also provided a unique opportunity for the researcher to collaborate with other experts in the field of OSH. In particular, the researcher collaborated with OPENNEXT colleagues from the University of Grenoble Alpes to co-author a conference paper titled "Identifying the Factors Affecting the Replicability of OSH Designs", which is presented in this thesis as paper B in section 4.

[7] https://opennext.eu/

1.4 Thesis overview

This doctoral thesis contains three main studies, each addressing one of the research aims, and is accordingly structured in three main sections. Table 1 offers an overview of this thesis by presenting the three main studies along with their corresponding DRM study type, relevant research aim, research questions addressed, methods used, relevant published papers and a description of the structure of the relevant section. This table can serve as a guideline for readers to refer to as a reminder of the thesis structure and content.

Table 1: Structure of this thesis.

PhD Thesis			
	Study 1	**Study 2**	**Study 3**
Relevant section	Section 2	Section 3	Section 4
Research Strategy (Von Krogh et al., 2012)	Distinguish, explore	Distinguish, design, explore	Distinguish, Explore
Predominant DRM study type (Blessing and Chakrabarti 2009)	Descriptive study I	Descriptive study I	Descriptive study I, prescriptive study
Research objective	Understand how success is defined in OSHD projects and compare it to NPD and OSS success	Understand the breadth of variety in OSHD projects by identifying project types.	Understand the meaning of replicability in OSH
Research question(s)	• What characteristics and practices are present in successful OSHD projects? • What metrics can be used to measure success in OSHD projects? • Does success look different in OSHD projects than in OSSD? • How does success in OSHD projects	• What are the main characteristics of OSHD projects? • What project 'types' can be identified based on the similarities and differences between the characteristics? • What insights can be drawn from these project types?	• What are the factors affecting the replicability of OSH? • What are the steps involved in replicating an OSH? • What project practices can be suggested for increasing the replicability of an OSH?

	compare to success in NPD project management?		
Method(s)	• Qualitative survey of 30 OSH practitioners • Thematic analysis	• Qualitative interviews with 3 experts • Thematic analysis •Manual qualitative data collection • Cluster analysis (quantitative)	• Qualitative survey of 30 OSH practitioners (same dataset as study 1) • Qualitative interviews with 15 OSH project founders and practitioners • Thematic analysis
Relevant published paper	Paper A (Antoniou et al. 2022)	N/A	Paper B (Antoniou et al. 2021)
Structure of section	Study presented in a published paper supported with a prologue and epilogue.	Study presented as a monograph section.	Study presented in a published paper supported with a prologue and epilogue.

To summarise, Study 1 is presented in Section 2, and addresses the first research objective by investigating the characteristics of successful OSHD projects; Study 2 is presented in Section 3, and tackles the second research objective through the development of a typology of OSHD projects; finally, Study 3 is presented in Section 4 and approaches the third research objective through identifying the factors that influence replicability of OSH and offering suggestions to OSHD practitioners for increasing the replicability of their projects. Each study addresses each research objective through a series of research questions and offers different contributions to knowledge and practice. Combined, the three studies all contribute towards the overarching research aim, to characterise the field of OSHD.

In terms of structure, Sections 2 and 4 include one published paper each, which are presented alongside commentary text (a prologue preceding the paper and an epilogue following it), while Section 3 is a monograph which forms the basis for a future research paper beyond the timeframe of this PhD project.

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Section 2. Investigating the meaning of success in OSHD projects

2.1 Prologue

While the literature sometimes talks about OSHD projects being successful or not, they do not actually define what constitutes success. Looking at other related fields, we find that Crowston et al. (2003, 2004) have contributed to the identification of success factors of OSS development projects. Iamratanakul et al. (2014) and Schuh et al. (2018), to name a few, identify and discuss success factors in closed source NPD projects. Hemetsberger & Reinhardt (2009) focus on success specifically in terms of collaboration in open source projects. While these and other authors make an invaluable contribution to knowledge in terms of success in different project contexts, the applicability of their findings to OSHD projects is unknown. Additionally, there are no rigorous research studies on the characterisation of success specifically in OSH projects.

A detailed literature review in Paper A, presented in section 1.1 demonstrates that there is a lack of research into the characterisation of success in OSHD projects. Additionally, little is known regarding the applicability of OSS and closed source NPD success factors in the realm of OSHD. The identified research gap is thus that there is a lack of knowledge on what constitutes success in OSHD projects and how success in these projects could be measured. This leads to the overarching research question:

What are the characteristics of successful OSHD projects and how can they be measured? What characteristics are unique to OSHD projects?

This question is then broken down into four research questions:

RQ1 What characteristics and practices are present in successful OSH projects?

RQ2 What metrics can be used to measure success in OSH projects?

RQ3 Does success look different in OSH projects than in OSS?

RQ4 How does success in OSH projects compare to success in NPD project management?

In section 1.1, these research questions are addressed through a research study presented as a paper published by the author and her collaborators in the journal *Design Science* titled “Defining Success in Open Source Hardware Development Projects: a Survey of Practitioners”. This paper offers a crucial first step in the research literature investigating the phenomenon of success in OSHD projects.

In this work, the following outputs are generated:

- A description of characteristics of successful OSH projects identified from a survey of practitioners
- A list of possible metrics for measuring OSH project success

- A comparison of project success characteristics from the OSS literature and the survey of practitioners
- A comparison between project success from the NPD project management literature and the results

This paper is preceded by a declaration of authorship (section 2.2), explicating the author's contribution to this work, and followed by an epilogue (section 2.4) which summarises the main findings of the work and links it to section 3 which follows.

2.2 Declaration of authorship

This declaration concerns the article entitled:										
"Defining Success in Open Source Hardware Development Projects: a Survey of Practitioners"										
Publication status										
Draft manuscript		Submitted		In review		Accepted		Published	x	
Publication details (reference)	Antoniou, R., Bonvoisin, J., Hsing, P.-Y., Dekoninck, E. and Defazio, D., 2022. Defining success in open source hardware development projects: a survey of practitioners. Design Science [Online], 8, p.e8. Available from: https://doi.org/10.1017/DSJ.2021.30.									
Copyright status										
I hold the copyright for this material	x	Copyright is retained by the publisher, but I have been given permission to replicate the material here								
Candidate's contribution to the paper	The candidate contributed about 95% of the research work for this paper. She predominantly executed the following: <u>Formulation of ideas:</u> The candidate originated the main vision for the study and the main steps taken. All other authors contributed ideas throughout, including how to specifically formulate the research questions, how to tackle certain aspects of the data analysis and how to best present the results, discussion and conclusions. <u>Design of methodology:</u> The candidate originated and developed the research idea and methodology. Dr Elies Dekoninck and Dr Daniela Defazio gave feedback throughout to ensure the methodology was sound. <u>Experimental work:</u> The candidate carried out the experimental work (survey and analysis). She prepared the survey questionnaire, reached out to potential participants and collected the responses. She transferred the responses to the qualitative data analysis software Nvivo, which she then used to code the responses using thematic analysis. Her supervisors contributed to the analysis by consulting on issues that arose. Dr Elies Dekoninck and Dr Jérémy Bonvoisin also contributed by performing an inter-coder reliability check which the candidate prepared. Dr Pen-Yuan Hsing helped pilot the inter-coder reliability check to improve the training materials. <u>Presentation of data in journal format:</u> The candidate wrote most of the manuscript and was the first author as well as the corresponding author for the journal. She wrote roughly 75% of the manuscript. The rest of the manuscript was written by Dr Pen Yuan Hsing, Dr Jérémy Bonvoisin, Dr Elies Dekoninck and Dr Daniela Defazio.									

Candidate Statement	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.		
Signed	Rafaella Antoniou	Date	11/08/2022

2.3 Paper A: Defining Success in Open Source Hardware Development Projects: A Survey of Practitioners

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2.3.1 Abstract

Recent years have seen the rise of citizens as contributors to hardware product creation. This trend has increased attention to open source hardware (OSH): a phenomenon that extends the intellectual property management and development practices in open source software (OSS) into the design of physical objects. OSH projects are different from OSS projects due to product type, and distinct from traditional closed source NPD ones due to their openness. These differences challenge the degree of applicability of existing project success definitions in the OSH context. To investigate project success in OSH, we conducted a qualitative survey with practitioners. We report characteristics of successful OSH projects through three identified themes: (1) value creation – the big-picture impact (2) quality of output – the quality of the hardware and accompanying documentation (3) project process – activities that contribute to success. We contextualise by comparing OSH with selected literature on the success of OSS and NPD project management. While our study confirms a similarity between OSS and OSH in defining project success, it also highlights themes that are uniquely important to the latter. These findings are helpful for OSH development practice and could provide lessons for OSS development and closed source NPD.

2.3.2 Introduction

In recent years, we have observed a proliferation of open source hardware (OSH) initiatives, with some developing profitable businesses. At the time of writing[8], the Open Source Hardware Association has certified 1663 OSH projects[9] and the Open Know-How search engine lists 486 OSH projects[10]. A 2018 study analysed over 200 OSH projects (Bonvoisin et al. 2018), while OSH business models have also been discussed in the literature (Pearce 2017; Li and Seering 2019). Pearce (2016) states that open source scientific hardware can achieve between 100% to 1000% return on investment after just a few months.

Success, in its traditional definition in common language, relates to the accomplishment of goals. Success criteria are important in any project, as they give its participants a focus for their efforts (Yu et al. 2005). Success criteria can help OSH communities "build effective forms of collective action and self-organisation" and "effectively create and capture value" (Troxler 2013). They can also aid in the formation of "a consistent identity and a set of commonly-accepted best practices" to help the OSH phenomenon become more mature (Bonvoisin et al. 2020). This is because employing best practices can help steer a project towards success (Griffin 1997).

Despite its relevance, there is a lack of comprehensive understanding of how success is defined in OSH projects, which has the potential to benefit both research and practice. A few publications attempt to suggest good practices or measures of impact (e.g. GOSH, 2016; Bonvoisin and Mies, 2018; van der Bij et al., 2013) but those only provide a partial view of success. This paper addresses this shortcoming by investigating how practitioners characterise success in OSH projects (objective 1) and identifying sim0ilarities and differences with other modes of product development (objective 2).

Firstly, we explore what characterises successful OSH projects, drawing insights from a qualitative survey of 30 OSH practitioners.

Objective 1: Understand success in OSH projects
To fulfil the first objective, we must answer the following research questions (RQs):
RQ1. What characteristics and practices are present in successful OSH projects?
RQ2. What metrics can be used to measure success in OSH projects?
To answer these questions, we collected and analysed data on the opinions of practitioners, who reflected on their experience with OSH projects. We define 'practitioner' as someone who has experience participating in an OSH project, has a real intention to do so or has research experience in the subject.

Secondly, to identify the distinctiveness of OSH project success, we compare our findings to characterisations of success found in selected open source software (OSS) and closed source NPD project management literature.

[8] 7 September 2021
[9] https://certification.oshwa.org/list.html
[10] https://search.openknowhow.org/

Objective 2: Identify aspects of success that are uniquely important to OSH projects
To fulfil objective 2, we asked the following RQs:

RQ3. Does success look different in OSH projects than in OSS?

RQ4. How does success in OSH projects compare to success in NPD project management?

We answered these RQs by comparing our findings with selected literature on OSS and NPD project management.

This paper proceeds as follows: section 2.3.2.1 reviews the selected relevant literature and describes the research gap addressed by the research objectives and questions. Section 2.3.2.3 summarises the significance of this research. Section 2.3.3 outlines the methodological approach for fulfilling the two objectives of the study. Section 2.3.4 presents the characteristics of successful OSH projects according to the opinions of the OSH practitioners surveyed (objective 1). Section 2.3.5 discusses the findings, compares them with OSS and NPD success (objective 2), and presents the study limitations and avenues for future work. Finally, section 2.3.6 concludes by summarising and highlighting the practical implications of this study.

2.3.2.1 Background and literature review

This section is devoted to laying the basis of our discussion and analysis. It starts by defining relevant concepts, including 'open source' (section 2.3.2.1.1), and 'project openness' (section 2.3.2.1.2), and how they apply to OSH projects. We then identify the gap in the literature by outlining extant research on success in OSH, OSS and closed source NPD (section 2.3.2.2).

2.3.2.1.1 What is an open source product[11]?

When a product is open source, it means that its users have four freedoms: (1) to use it for any purpose, (2) to study it, (3) to make and redistribute copies of it, and (4) to make changes to it and share them (Stallman 2002). The articulation of these fundamental freedoms originated in the early days of software development when developers openly shared source code and built on each other's work (ibid). Software that respects these freedoms through open source licensing is referred to as OSS. There are many examples of OSS, including the Mozilla Firefox web browser[12], the WordPress content

[11] In this paper we use terms like 'open source products' and 'open source hardware' without hyphenation between the words 'open' and 'source'. Grammatically, compound adjectives must be hyphenated (e.g. 'high-quality hardware'). However, many published works (e.g. the Open Source Hardware Definition by the Open Source Hardware Association) do not hyphenate 'open source'. We chose here to not hyphenate because we acknowledge the non-hyphenated expression 'open source' as a de facto standard. Additionally, 'open source X' can be wholly thought of as a noun rather than a compound adjective and a noun since we are referring to a particular phenomenon.

[12] https://www.mozilla.org/firefox/new/

management system[13], and the Linux kernel[14] on which many enterprise and mobile operating systems are based.

These freedoms are also reflected in OSH. Specifically, the definition of OSH by the Open Source Hardware Association (2018) states that "[OSH] 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".

While access to source code is needed to practice those freedoms for software, what constitutes the 'source' of OSH is less well-defined (Bonvoisin, Mies, Boujut, et al. 2017). More recently, the OSH specification DIN SPEC 3105 (*DIN SPEC 3105-1:2020-09, Open Source Hardware - Part 1: Requirements for technical documentation*) describes the requirements for what constitutes an adequate 'source' in OSH. It also transposes the four freedoms of open source into the four 'rights' of OSH: the right to study, to modify, to make and to distribute (Bonvoisin et al. 2020), in line with the OSH Definition (Open Source Hardware Association 2018). For this paper, we consider the source to be all necessary documentation – such as blueprints, computer-aided design (CAD) files, or bills of materials (BoMs) – which enable a person to exercise the four rights of OSH.

Prominent examples of OSH include the RepRap 3D printer[15], the AudioMoth environmental sensor[16], the Opentrons lab automation system[17], and the FOSSASAT[18] series of satellites first launched into space in December 2019[19]. The achievements of OSH projects have garnered academic interest, as reflected by the emergence of peer-reviewed journals dedicated to OSH such as the Journal of Open Hardware and HardwareX. The development of OSH is a unique type of product development that enables the incorporation of users in the design process. Thus, it is a highly relevant topic in design science (Papalambros 2015).

2.3.2.1.2 Product vs process openness

The OSH phenomenon is co-occurring with a "paradigm shift in industrial value creation", which is often observed through novel processes that are outside the umbrella of traditional economics (Moritz et al. 2018). These processes, which include "networking, knowledge sharing, collaboration, co-creation and decentralisation" (ibid), are part of the 'bottom-up economics' concept (Wulfsberg et al. 2011).

The emergence of OSH sets the scene for new, 'open' product development practices: participative, democratic, community-based, and open to the participation of any interested person, regardless of background. OSH development projects (hereinafter

[13] https://wordpress.org/
[14] https://www.linuxfoundation.org/
[15] https://reprap.org/wiki/RepRap
[16] https://www.openacousticdevices.info/audiomoth
[17] https://opentrons.com/
[18] https://fossa.systems/
[19] https://en.wikipedia.org/wiki/List_of_Electron_launches#2019

referred to as OSH projects) can be characterised by their degree of openness, which has three factors (Balka et al. 2014):

1. Transparency: any person can have unrestricted access to product information
2. Accessibility: any person can take part in the product development process
3. Replicability: any person can physically reproduce the product if following the design guidelines

Additionally, Huizingh (2011) identified two types of 'openness': product openness and process openness. These relate to transparency, accessibility and replicability and indicate that they are not binary states, but rather lie on a spectrum. In other words, OSH projects have a certain *level* of transparency, accessibility, and replicability.

Product openness refers to how much of the design documentation (CAD files, BoMs, etc.) of the final product are open source as defined in section 2.3.2.1.1. The two extrema of the spectrum of product openness are closed source hardware and OSH. The former are physical products for which no documentation is publicly available, and people are not allowed to make and distribute copies or make changes to the designs. The latter are products for which all design documentation is available with open source licensing (Bonvoisin et al. 2018), therefore granting the public the four freedoms of open source (section 2.3.2.1.1). Product openness relates to transparency and replicability as defined by Balka et al. (2014).

Process openness relates to the 'intention' of assembling a group of voluntary participants to take part in the design process. To have process openness in a project, there must be product development processes that allow interested persons to participate (Bonvoisin et al. 2018). Design projects lie within a spectrum of process openness, with the extrema being completely closed design and completely open design. The latter involves product development which is open to participation by any external person, while the former allows no external participation at all. Process openness relates to accessibility according to the definition of Balka et al. (2014).

The Open Source Hardware Association (2018) 49efinetion and DIN SPEC 3105 have requirements for product openness only, with process openness left as an optional best practice. However, Bonvoisin and Mies (2018) proposed a tool called Open-o-Meter, which does use process *and* product openness criteria, for assessing the extent of openness of an OSH project. The relevance of process openness for project success should be further explored.

2.3.2.2 Literature gap

Research regarding the development of OSH is still in its infancy. The limited number of published studies that exist have focused on describing this field and highlighting emerging issues. Boisseau et al. (2017) propose a design process model using a grounded theory approach; Bonvoisin et al. (2018) investigate participation in OSH projects; Dai et al. (2020) highlight issues in knowledge management of OSH communities; and Balka et al. (2009) compare OSH development to OSS development and present project characteristics.

However, when it comes to OSH project success, there is currently very little literature. Some effort has been made to standardise technical documentation for OSH projects i.e., DIN SPEC 3105. This could be related to success, but is only limited to technical documentation, not other project practices. Moritz et al. (2018), though aiming to identify best practices in OSH projects, effectively provide merely a description of OSH projects and companies (e.g. licensing selection, community size, community roles). Bonvoisin and Mies (2018) present the Open-o-Meter, a tool for measuring the 'openness' of an OSH project, which offers only a partial view of what might constitute success. The Open Impact Toolkit provides a set of metrics for measuring the impact for OSH projects (GOSH 2016). It gives some interesting examples of what factors (in the form of metrics) could affect 'project impact', such as usage of the hardware and derivative works. However, its definition of 'project impact' is vague, and the metrics were not rigorously derived. Van der Bij et al. (2013) suggest that the following practices make OSH 'work': "be open"; "make the design general enough"; "use standards and contribute to them"; and "be complete: from design to production test and drivers". However, these suggestions are limited in that they are derived from the experiences of the authors who are from the same organisation and only develop open source electronics hardware.

In summary, while some work has been done on standardising documentation or describing best practices to produce 'impact', there is little work directly studying which features characterise the success of OSH projects in terms of both process *and* product. In the next sections, we highlight the gap in the literature which our study aims to fulfil, through the presentation of selected literature on success in OSS development (section 2.3.2.2.1and closed source NPD (section 2.3.2.2.2).

2.3.2.2.1 Comparison with OSS development

Open source development has its origins in software, before its more recent expansion into hardware (Bonvoisin et al. 2018). What contributes to OSS project success has received significant attention, while this is not the case for OSH. Aksulu and Wade (2010) highlight studies that investigate determinants of OSS development success, and the potential relationships between them. Crowston et al. (2003) describes the development of success factors in OSS through literature reviews and practitioner opinion, and later investigate relationships between different success factors (Crowston et al. 2004). The Core Infrastructure Initiative (n.d.), a Linux Foundation project, has created a 'best practices criteria' self-certification badge programme to help OSS projects employ practices that relate to producing higher quality software (which relates to success). Examples of best practices include having a bug reporting process and using a publicly readable repository for storing files which enables version control[20]. Such practices

[20] tracking and managing changes to files

could also be relevant in OSH projects, suggesting merit in comparing the two. Raasch (2011) suggested that when more practical applications of open design proliferate, research can illuminate the differences between OSH and OSS development – in this sense our study is timely.

While both OSH and OSS projects result in products with which a user interacts, there are substantial differences between hardware and software which influence the development process (Dai et al. 2020). Hardware are physical objects which are difficult and costly to change by the producer after manufacturing and distribution to end users, whereas software is flexible with newer iterations able to propagate with relative ease via software updates. Also, hardware development is more complex than software development as the former involves more considerations such as manufacturing, tooling, supply chain management. These discrepancies suggest differences in what constitutes success in OSH projects compared to OSS projects.

Crowston et al. (2003) identify a list of what they call 'success measures', characteristics of a project which influence how successful it is. Other studies on OSS investigate only a few specific characteristics of projects, e.g. Sen et al. (2012) investigate the number of developers and its determinants, whilst Midha and Palvia (2012) explore project popularity and developer activity. The seminal study of Crowston et al. (2003) on OSS project success is conceptually similar to our study and is the most appropriate point of comparison for our work as it focuses on the project level and success in general, rather than one or two specific project success characteristics.

2.3.2.2.2 Comparison with closed source NPD

Closed source value capture mechanisms in the NPD literature revolve around restricting product design through patents and secrecy (James et al. 2013), whilst OSH projects share their designs publicly, allow reuse via modification and/or duplication, and are characterised by transparency. In addition, in closed source NPD, a company tends to keep the design process exclusive to its employees, while, in contrast, certain OSH projects accept and encourage external participation. Furthermore, the motivations of participants and project organisations are likely to be different between closed source and open source development, which could impact project success. For example, in OSS projects, some people contribute not for financial gain, but to improve their skills (Hars and Ou 2001) – as is also the case in OSH (Hausberg and Spaeth 2020). A study on organisations based on OSH found that they are motivated not just by technological (e.g. standardisation), economic (e.g. research and development cost reduction) and product-based reasons (e.g. distribution permission), but also intrinsic factors such as personal satisfaction, altruism, hacker ethic and reciprocity (Li et al. 2017).

These differences in the development process and participant motivations could translate into a different view of what a successful project in each mode of development looks like. However, despite the contrasts outlined above, we expect that some insights from closed source NPD project management literature on project success, and some best practices, would apply to OSH projects.

Some project management literature on closed source NPD discusses success at the company level (Cooper and Kleinschmidt 1995) such as strategic success in innovation. However, our study is focused on what constitutes success within a project and comparisons are made to literature at this level.

In project management, the traditional way of evaluating project success is through the 'triple constraint', also known as the 'iron triangle', which contains three key dimensions: time, cost, and quality (Atkinson 1999). These dimensions relate to whether the project was completed on or ahead of time; within or under budget; and at the expected or higher quality. Usually, trade-offs occur between these dimensions.

Instead of the simplistic iron triangle, Shenhar and Dvir (2007) suggest five main dimensions of project success: efficiency, impact on the customer, impact on the team, business and direct success, and preparation for the future. Dvir and Shenhar (2011) later identified seven characteristics of successful projects, namely (1) they create competitive advantage and stakeholder value, (2) a long time was taken to define them: creating a strong vision, clear need and choosing the most suitable execution approach, (3) they create revolutionary project culture, (4) they have highly qualified project leaders who are supported by top management (5) they maximise the use of existing knowledge, often in cooperation with outside organisations, (6) they have integrated development teams which are adaptive and have quick problem-solving skills, and (7) they have teams with "strong sense of partnership and pride".

The closed source NPD literature is vast, with hundreds of papers and books written on the topic. For our study, we narrowed down the literature to only highly cited works that focus on NPD project-level success and where the descriptions of success characteristics are at an equivalent level of granularity to our dataset. As such, in section 2.3.5.1.2 we compare the results with the iron triangle (Atkinson 1999), the five dimensions of project success (Shenhar and Dvir 2007) and the seven characteristics of successful projects (Dvir and Shenhar 2011).

2.3.2.3 Significance

To summarise, there is a lack of studies examining success in OSH projects. To our knowledge, our research is the first to directly survey OSH practitioners with the aim of deriving common themes on what is considered success at the project level in terms of both process *and* product. We compare our findings to those in the OSS and NPD literature and identify success characteristics unique to OSH projects. This work is not only useful for furthering the study of OSH projects and but can also inform the OSS community or even closed source NPD.

2.3.3 Method

The first objective of the study, understanding success in OSH projects, was addressed by qualitative analysis of OSH practitioner responses to an open-ended question survey.

Their opinions were used to identify the success characteristics of such projects and potential metrics for measuring success. The second objective, identifying aspects of success that are uniquely important to OSH projects, was fulfilled by comparing the results with selected relevant literature.

2.3.3.1 Survey design

Conducting a survey with open-ended questions is an effective method for collecting people's opinions and experiences. To identify the characteristics of successful OSH projects, a written survey was designed and conducted to extract them from the experiences of practitioners.

The survey collected opinions on success factors, potential success metrics and essential practices in OSH projects. In combination, these would give a characterisation of project success in the context of OSH development, the main aim of this study.

The first round of the survey took place in February 2020 at an in-person academic workshop[21] focusing on OSH, where the respondents individually wrote down answers to the questions in physical (paper) format. Since most of the participants of that event were academics, a second round of the survey was conducted in digital format using an online survey tool, to reach a broader audience. This was disseminated through social media channels related to OSH, for example, the Twitter hashtags #opensourcehardware and #opensource as well as one of the author's Twitter profile, who has a following of OSH practitioners and researchers from a variety of backgrounds such as designers, scientists, mechanical and software engineers; institutions such as OSH electronics manufacturers, distributors and collectives for developing collaborative solutions using OSH; and projects developing various types of hardware. The survey was live from 12 February to 30 April 2020. To screen for each respondent's experience with OSH projects, they were asked to indicate whether they had participated in none, one or multiple OSH projects. They also provided their names and emails.

The following three open-ended questions were asked, each followed by a blank text box in which the respondents could write their answers.

1. What does OSH project success mean to you? i.e., examples of success factors (relates to RQ1)
2. What are some potential metrics for OSH project success? i.e., what could be used to measure success (relates to RQ2)
3. What practices do you consider essential to successful OSH projects? i.e., activities, artefacts (relates to RQ1)

2.3.3.2 Survey responses and demographics

We obtained 30 written survey responses: 10 responses from attendees of the academic workshop on OSH (30 participants at the workshop in total, therefore 33%

[21] https://www.bath.ac.uk/announcements/open-hardware-from-academia-recap-on-international-workshop/

response rate) and 20 responses via the online version. The responses varied in length, from some with short, bullet-point answers and others with long paragraphs of text. According to Mason (2010), the sample size is satisfactory for saturation. We also observed repetition in the data, which is demonstrated by the number of respondents who talked about each success characteristic (shown in section 2.3.4). This also indicates data saturation.

The demographic of respondents can be described as follows: 8 had participated in one OSH project; 18 had participated in more than one; and 4 had participated in none, but had research experience on the topic, or had the intention of publishing their hardware designs under an open source license.

2.3.3.3 Data analysis and validation

The chosen data analysis method for the survey was thematic analysis, which involved coding the data set without a pre-existing framework. This was done to place a focus on the informants (Gioia et al. 2013), without imposing any pre-existing ideas about success from the literature. Consequently, the themes relating to the success characteristics of OSH projects are as close as possible to the data itself, thus reducing bias. The analysis was conducted using the qualitative data analysis software Nvivo 12.

Certain practices can lead to success factors through their cause-and-effect relationship. In addition, metrics can measure practices and success factors. This logical relationship between success factors, practices and metrics, combined with the fact that the respondents often did not make a distinction between them in their responses, lead to the responses to the survey questions being treated as one dataset during the analysis. This allowed the distillation of key themes from the dataset, with a large number of responses coded in each. This then enabled the results to be consolidated into the characteristics of successful OSH projects, and a list of metrics associated with them (see section 2.3.4).

The generation of themes is a key feature of qualitative research and is dependent on the depth of understanding of the researcher. This is subsequently influenced by the researcher's familiarity with the data sets and the research topic (Holton and Walsh 2017). Therefore, the coding was conducted iteratively, which increased this depth of understanding through the data analysis process. This also ensured that all the themes were captured, errors were reduced, and a rich description of the themes was achieved.

Where appropriate, in vivo codes[22] were used to stay close to the original data. Initial, intermediate, and advanced coding were used, with increasing familiarity with the data. Initial coding involved basic fracturing of the data, intermediate coding involved grouping of the codes and transformation into themes, while advanced coding involved abstracting the highest-level themes, i.e. characteristics (Chun Tie et al. 2019).

[22] the respondents' verbatim quotes used as codes themselves.

The coding was primarily performed by a single researcher. To ensure validity, their coding was compared to that of two other senior researchers. The coding was tested both in breadth (the success characteristics) and in depth (the themes within one of the characteristics). The results of the test were calculated in percentage agreement (Caro et al. 1979) using equation 1. Percentage agreement is a frequently used metric for inter-coder reliability tests using nominal data and was used in similar research such as that of Crowston et al. (2003). Agreement above 70% was achieved, which is considered sufficient to demonstrate the reliability and validity of the coding framework (Multon and Coleman 2018).

$$Agreement\ [\%] = \frac{number\ of\ agreements}{number\ of\ agreements + number\ of\ disagreements} \times 100\% \qquad (1)$$

The outcome of the analysis includes several characteristics of successful projects and metrics for measuring some of them. These were grouped into three top-level themes: value creation, quality of output, and project processes.

2.3.4 Results: Characteristics of successful OSH projects

From the thematic analysis of the survey responses emerged three different but related themes regarding what characterises successful OSH projects: value creation, quality of output, and effective processes. These themes influence each other: processes can influence quality of the output, and the quality of the output can influence value creation. This is summarised in Figure 7.

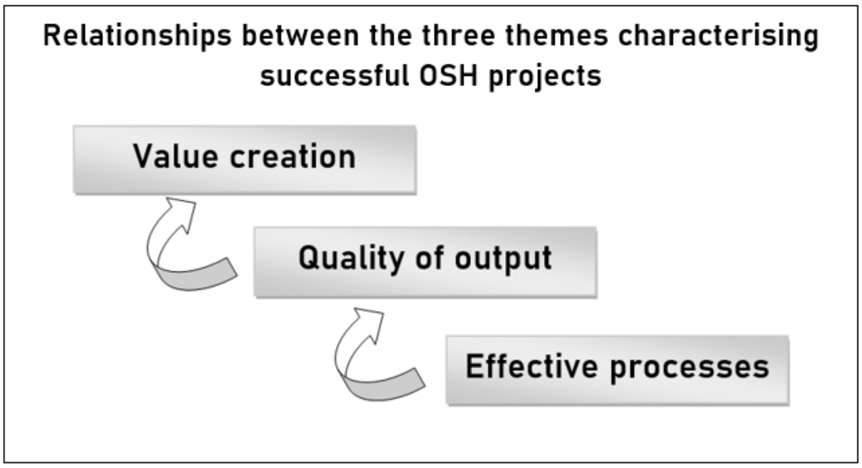

Figure 7: Relationships between the three themes identified from the thematic analysis of the survey responses.

In sections 2.3.4.1, 2.3.4.2 and 2.3.4.3, we describe these three themes through the insights derived from the data, delving into detail about what characterises successful OSH projects within each theme. In section 2.3.4.4, we summarise the characteristics of successful OSH projects in the form of a table and provide suggestions for corresponding success metrics based on the data.

2.3.4.1 Successful OSH projects create value

This section presents the results from the survey responses which relate success to creating value, with 29 responses coded in this theme. Value refers to benefits, i.e., positive outcomes or things of perceived importance. The respondents believe that successful projects create value to contributors, users, other projects, and society. They also generate business activity and are sustainable over time. Popularity and a good reputation can indicate that they create value. Respondents also mentioned that popularity and reputation can be demonstrated by the ranking of projects on search engines; the number of project, documentation, and scientific paper citations; the number of views and downloads of project documentation; the number of followers/interested people; and the presence of project communities with a high level of activity, e.g., frequent participation in community forums. The following sections describe the types of value creation which were identified from the survey data.

2.3.4.1.1 Successful OSH projects create value to people and other projects

All 29 respondents, whose answers were coded in the top-level theme (section 2.3.4.1), believe that successful projects create value specifically to people and other projects, with the majority referring to a large and vibrant community around a project to be indicative of success.

Successful OSH projects create value to contributors by way of personal gratification through "getting acceptance" by a community of users and satisfaction through creating something useful for others. They also generate value to contributors by giving them career impact, such as academic impact from paper publications and citation rates, as well as progression and development within the projects. As a result, contributors are motivated, interested and engaged in the projects, demonstrating long and continuous contribution. A potential metric for this is the number of third-party contributions, i.e., contributions from people outside the core team of originators. Additionally, by creating value to contributors, projects can become more attractive to new ones, which could be indicated by the number of people who want to contribute – for example by counting the number of forks of a project repository.

Successful OSH projects provide value to their users, which could be assessed by measuring how many people need the hardware those projects develop i.e., the market size for that hardware. In addition, the hardware produced by successful projects is helpful and useful to its users, is used and retained for a long time, while also being used in creative ways that were potentially not envisioned by the originators. Creating value to users can be indicated by their level of satisfaction with the hardware; their level of interest in the project; a high level of use, which could be measured by the number of units in use; the number of users (including those who built the hardware themselves); and a diverse user community (particularly including groups who did not have access to that technology before using the OSH).

Successful OSH projects create value to other projects. Several respondents believe that successful projects provided a basis for derivative projects and hardware, so the presence of such derivatives or “remixes” is an indicator of success. The number of derivatives as well as “successful derivatives” (as stated by the respondents) could be metrics of success for projects.

Successful OSH projects create value to society by contributing to “moving the state of the art forward incrementally” in technology, science, and public health. They also allow others to learn, and they contribute to improving access to knowledge.

2.3.4.1.2 Successful OSH projects generate commercial value

The generation of business activity was identified as a characteristic of successful OSH projects, with 8 respondents referring to it. It was stated that business aspects of projects should be “fostered and encouraged” in OSH. There were references in the data relating success to having a sustainable business; enabling commercial use through a relevant license; selling hardware units or kits which are easily accessible; and generating revenue and profit.

Financial gain in the form of revenue and profit indicates a successful business and thus a successful project. It is closely related to the number of units sold, which could be a metric of success. Having independent vendors (other than the originator(s)) making and selling the hardware or its variants, as well as units selling well on the market for several years also indicate success.

2.3.4.1.3 Successful OSH projects create value sustainably

7 respondents referred to project sustainability as being important to success. Project sustainability means that project activity could continue without the originator(s). Sustainability could be demonstrated by having funds available to conduct project operations, or actively planning for continuity of the project. A specific indicator of project sustainability mentioned in the data was the ‘bus factor’. The ‘bus factor’ indicates how many people would have to step down from the project (metaphorically ‘be hit by a bus’) for the project to be unable to continue (Cosentino et al. 2015). Project sustainability is intrinsically linked to those that have a sustainable business. These are projects in which the business activity can continue and be maintained over time at the present level or higher.

2.3.4.1.4 Successful OSH projects create value to the open source movement

One respondent believes that successful projects contribute to the goals set in the GOSH Roadmap (Global Open Science Hardware 2018) whose aim is to make open science hardware ubiquitous by 2025. This characteristic is thus only applicable to OSH primarily designed for scientific applications. However, some of the goals could possibly apply to other types of OSH. This includes creating financial support structures for open science hardware, as well as preparing guidelines for different stakeholders (e.g., for compliance, licensing, and documentation).

2.3.4.2 Successful OSH projects create high-quality outputs

27 respondents believe that successful OSH projects produce high-quality outputs in the form of hardware and documentation. The two are often related to each other.

Some characteristics identified within this section relate to features relevant to definitions of OSH projects, such as that of the Open Source Hardware Association (2018). However, there is a *degree* to which these features can be implemented, which the respondents believe relates to project success, hence they are included in the results.

2.3.4.2.1 Successful OSH projects create high-quality hardware

Hardware quality, referred to by 16 respondents appears to be important to success. The "quality of the initial contribution" was suggested as an indicator of success. Successful projects create hardware which are performant and highly accessible, reproducible, and modifiable. Their designs are also characterised by high transparency.

Successful OSH projects develop highly accessible hardware. Open standards and widely available tools are used as much as possible for production (e.g., manufacturing and assembly).

At least a prototype is available, and hardware units are being sold and easily accessible. The design and development of the hardware has proceeded enough to produce at least a prototype, which can be either made by individuals or bought. Ideally, completed units and/or kits are available for sale, and access to them is easy.

Successful OSH projects develop highly reproducible/replicable hardware. Replicability relates to whether external people can build the OSH using the documentation and raw materials. This can be demonstrated by the presence of individuals external to the projects who have built a working version of the hardware. The respondents mentioned ease of replicability in particular, which could be influenced by the quality of documentation (see section 2.3.4.2.2) as well as the availability of raw materials in the location of the person reproducing it.

Successful projects develop highly modifiable hardware. The hardware can be modified and adapted. This could be demonstrated by having evidence of others modifying the hardware to suit their unique purposes (e.g., by changing dimensions, materials, colours, etc.) or by adding new features (e.g., creating extensions, add-ons, etc.). The level of modifiability is influenced by a variety of factors including the presence of editable documentation (section 2.3.4.2.2).

Successful OSH projects develop performant hardware. When asked about what makes a successful OSH project, multiple respondents answered with a variant of "does [the hardware] work?" According to a specific respondent, a milestone is when the hardware becomes operational to relevant standards. The hardware must also be able to perform its intended function and have reliable performance.

Successful projects create highly transparent hardware designs. This could be demonstrated by projects selecting the most suitable open source license for the projects and the hardware. Successful projects also fully disclose their designs with sufficient detail to enable any person with the relevant skills to build the associated hardware artefact. They further increase the level of transparency by ensuring it is easy for someone to build the hardware and understand how it works. This additionally contributes to the levels of accessibility and replicability.

Successful OSH projects develop hardware that solves a problem/fulfils a need and offers advantages over alternative products. The hardware "scratches an itch", i.e., solves a problem or fulfils a need of the user. Examples of this might be by providing a feature advantage over other products; giving them access to technology previously unattainable to them; offering a better-quality output; fulfilling a need or providing features that did not previously exist; or being more affordable than other offerings.

2.3.4.2.2 Successful OSH projects create high-quality documentation

Documentation quality is also important to success, with 25 respondents referring to it.

Successful OSH projects ensure the hardware source is highly accessible. The documentation is published on publicly accessible platforms such as GitHub[23] or GitLab[24] (commonly used version control repository-hosting platforms for open source projects) and is easy to find and download. The hardware source is also highly accessible in the sense that design and documentation files use open file formats, therefore not requiring the use of closed source software. The level of accessibility of hardware documentation can influence replicability and modifiability.

Successful OSH projects create documentation that is complete and has broad coverage. All the necessary documentation types are present, for at least a prototype of the hardware, such as BoMs, CAD files, design process documentation, and user manuals. These influence the level of hardware replicability. Lessons learnt are tracked and could be captured in one or more documents. Such documents contain a log of the lessons which have the potential to be carried over to future or other parallel projects. These lessons could be technical or organisational. Successful OSH projects also have media and scientific publications. One survey respondent commented that the communication skills demonstrated in documentation could affect the level of usage of a project and its hardware.

Successful OSH projects create highly editable documentation. This means that people can easily make changes to it, which in turn increases the modifiability of the hardware.

2.3.4.3 Successful OSH projects have effective processes

This section presents the results from the survey which relate to the activities and processes that are part of successful OSH projects. The main finding was that successful projects have high process openness and follow product development, project,

[23] https://github.com/
[24] https://about.gitlab.com/

community, and business management good practices. They are active, transparent, and committed to openness by sharing as much information as possible. 28 respondents referred to the different project activities facilitating success coded in this theme.

2.3.4.3.1 Successful OSH projects follow good product design and development practice

17 respondents believe that good product design and development practice is important for success in OSH projects.

Successful OSH projects move through product development stages rapidly. This indicates a high level of activity. Certain respondents mentioned that successful projects have moved beyond the ideation stage: they are ready for use and are being manufactured and easily accessible.

Successful OSH projects develop hardware using good design practice. The survey respondents think good practice includes ensuring backwards compatibility of hardware versions and software; releasing a first version which is a minimum viable product (enabling the collection of feedback on the hardware); designing the hardware to be user-friendly and made of modular components; making prototypes; using CAD tools and using scientific reasoning for decision making. The number of design solutions considered as well as the number of design iterations were also mentioned as potential metrics of success relating to good design practice.

Successful OSH projects have design and development processes that enable product openness. The respondents think that successful projects use parametric design methods to facilitate customisation and enable modifiability, which in turn increases openness. They also mentioned that the availability of raw materials around the world should be considered by hardware designers to increase replicability. The ability to build the hardware using “everyday tools” would also facilitate replicability.

Successful OSH projects develop hardware using user-centred design. The data showed that successful projects design their hardware with their users in mind.

2.3.4.3.2 Successful OSH projects have effective management and teamwork

22 respondents believe that effective project management and teamwork are important for success in OSH projects.

Successful OSH projects are managed effectively. They demonstrate effective project management by using version control software (platforms enabling the recording of file changes over time); having traceable contributions; following clear aims; having ‘good governance’; and being actively maintained. The latter could be measured using the time taken to close issues that are flagged up in the project repositories.

Successful OSH projects effectively engage and manage their user and follower communities. They foster a vibrant community of users and followers, make an effort to build a user and follower community, and exhibit frequent and clear communication and support. For example, a successful project might have a website where the project is introduced and explained, and an online forum for community participation and support. Successful projects additionally engage their user and follower community by participating in community events such as workshops.

Successful OSH projects engage potential contributors, and existing ones work together effectively. They actively engage contributors by making contributions easy. They do so by documenting the design, the decision-making process and the lessons learnt, which assists future work. Successful projects document early on and have contribution policies and structured knowledge bases for contributors. They also adopt contributed modifications. A successful project's contributors share similar expertise, contribute in diverse ways (e.g., designing, bug fixing), and demonstrate effective collaboration, co-creation, and teamwork. The number of people who contribute to a project, including the presence of commercial/industry contributors could indicate success.

2.3.4.3.3 Successful OSH projects are committed to openness

The respondents believe that successful OSH projects engage "openly and transparently" and fully disclose information. 13 respondents believe that successful projects must be committed to openness.

Successful OSH projects develop hardware and documentation using an open source toolchain. This relates to the use of OSS for creating computer aided design (CAD) files, manufacturing files, and any associated documentation and software.

Successful OSH projects track lessons learnt and publicly share them, indicating a level of knowledge management and a means to transfer knowledge across projects.

Successful OSH projects enable commercial use. They do so by publishing their source files with an open source license that enables commercial use.

Successful OSH projects are committed to openness even on occasions where it might be opposed by certain external forces. Respondents identified the need for a commitment to openness for success as some had experienced some barriers to being open source, such as "commercial expectations" and "cost". They may also have been referring to cases such as MakerBot[25] which changed to closed source after initially being open source. Additional commitment to openness seen in successful projects is the use of OSS to conduct their everyday activities.

2.3.4.4 Summary of results

In Table 2, we provide a summary of the characteristics of successful OSH projects described in sections 2.3.4.1, 2.3.4.2 and 2.3.4.3, and give a list of metrics for measuring progress towards them. We have identified a total of 101 metrics. Most of the metrics

[25] https://www.makerbot.com/

are uniquely linked to each characteristic, however, two of them (presence of commercial use license and presence of lessons learnt log) relate to more than one.

Table 2: Summary of characteristics of successful OSH projects along with potential metrics for measuring them.

Project success characteristics	Potential metrics	
Successful OSH projects create value (29 unique respondents) ○ **Successful OSH projects create value to people and other projects (29 respondents)** ○ **Successful OSH projects generate commercial value (8 respondents)** ○ **Successful OSH projects create value sustainably (7 respondents)** ○ **Successful OSH projects create value to the open source movement (1 respondent)**	ranking of project on search engines	number of units in use
	number of project citations	hardware retention by users
	number of project documentation citations	diversity of user community
	number of scientific paper citations related to the project	presence of project/hardware derivatives
	number of views of project	number of project/hardware derivatives
	number of downloads of project documentation	presence of project/hardware successful derivatives
	number of followers/interested people	number of project/hardware successful derivatives
	level of activity of project community	presence of commercial use license
	level of participation in community forums	level of revenue generated
	level of contributor satisfaction	level of profit generated
	length of contributor participation in project	number of hardware units/kits sold
	number of third-party contributions	number of hardware units/kits sold over time
	number of people who want to contribute	presence of vendors other than the originator(s) making and selling the hardware or its variants
	number of forks (copies) of project repository	level of funding available to the project
	market size of hardware	presence of planning for project continuity
	level of user satisfaction	level of project bus factor
	number of users	level of contribution to Global Open Science Hardware (GOSH) goals
	level of usage of hardware by users	

Project success characteristics	Potential metrics	
Successful OSH projects create high-quality outputs (27 unique respondents) ○ **Successful OSH projects create high-quality hardware (16 respondents)** ○ **Successful OSH projects create high-quality documentation (25 respondents)**	level of accessibility of hardware	level of reliability of hardware performance
	level of usage of open standards	level of advantages the hardware has over other similar offerings
	level of availability of tool(s) required to produce the hardware	level of accessibility of the documentation
	presence of at least a prototype of the hardware	level of transparency of documentation
	presence of hardware units/kits for sale	level of communication skills demonstrated in documentation
	level of accessibility to hardware units/kits for sale	presence of design process documentation
	presence of individuals external to the project who have built a working version of the hardware	presence of bill of materials
	level of reproducibility of the hardware	presence of CAD files
	level of availability of hardware raw materials at the location of people who want to replicate it	presence of user manual
	level of modifiability of the hardware	presence of lessons learnt log
	number of people who have modified the hardware for their own purposes	presence of media and/or scientific publications of hardware/project
	presence of a working version of the hardware	presence of editable files
	presence of a version of the hardware which operates to relevant standards	

Project success characteristics	Potential metrics	
Successful OSH projects have effective processes (28 unique respondents) ○ **Successful OSH projects have effective management and teamwork (22 respondents)** ○ **Successful OSH projects follow good product design and development practice (17 respondents)** ○ **Successful OSH projects are committed to openness (13 respondents)**	level of process openness in the project	number of contributors
	use of version control software	presence of commercial/industry contributors
	level of traceability of contributions	speed of progression through product development stages
	level of clarity of project aims	level of project activity
	level of quality of project governance	stage of product development process
	level of activity of project maintenance	presence of backwards compatibility between versions of the hardware and software
	issue closure time	presence of minimum viable product (MVP)
	frequency of communication with community	level of user-friendliness of hardware
	level of clarity of communication with community	level of modularity of hardware
	presence of project website	presence of prototypes made
	presence of project description on project website	level of use of CAD tools
	level of participation in community events	number of design solutions considered
	level of ease of contribution to project	number of design iterations
	presence of design documentation	use of parametric design
	presence of decision-making process documentation	level of consideration of global raw material availability
	presence of lessons learnt documentation	level of ability for someone to build the hardware using widely available (i.e., not specialised or inaccessible) tools
	presence of contribution policy	use of user-centred design
	presence of structured knowledge base for contributors	level of disclosure of information regarding the project and hardware
	level of adoption of contributed modifications	use of open source toolchain for all types of documentation and project activity
	level of similarity of expertise between contributors	presence of lessons learnt log
	types of contributions submitted	presence of commercial use license
	level of collaboration, co-creation and teamwork	

2.3.5 Discussion of findings

In this section, the characteristics of successful OSH projects presented in section 2.3.4 are discussed. In section 2.3.5.1, we compare the results with OSS literature and NPD project management literature before analysing aspects of success uniquely important to OSH in section 2.3.5.2.

2.3.5.1 Comparison of findings with selected relevant literature

This section presents a comparison of the results presented in section 2.3.4 with OSS literature (section 2.3.5.1.1) and NPD project management literature (section 2.3.5.1.2).

2.3.5.1.1 Comparison with OSS literature

There is a similarity between our results on OSH success and literature on OSS success. The results confirm the non-software related 'success measures' identified by Crowston et al. (2003), such as number of contributors/developers, level of activity, bug fixing performance, number of downloads, design/code reuse, user and project member positive outcomes (satisfaction, reputation etc), process quality, and software/hardware quality. Table 3 summarises that comparison.

Table 3: Comparison of the results of the presented study with that of Crowston et al. (2003) on OSS project success.

Category (adapted from Crowston et al. (2003))	**Success measures (adapted from Crowston et al. (2003))**	**Comparison with the responses in the current study**
USER	Users are satisfied (user ratings, opinions on mailing lists and user surveys).	Product users being satisfied was confirmed in our study. However, those methods of assessing satisfaction were not mentioned.
	Users are involved	Confirmed
PRODUCT	Product quality	Confirmed
	Documentation quality	Confirmed, however, our study goes into much further detail about what constitutes high-quality documentation.
	Product fulfils intended purpose	Confirmed
	Code and documentation are organised, clear and maintainable	Code maintainability is software related and thus not addressed in our study. Clarity and effective communication in the documentation was confirmed in our study, but the documentation being organised was not explicitly mentioned, however it makes sense that this would apply to OSH as well as OSS.

Category (adapted from Crowston et al. (2003))	Success measures (adapted from Crowston et al. (2003))	Comparison with the responses in the current study
	Software is portable to and compatible with other systems and programs	While this is specific to software, backwards compatibility was also mentioned in our study. Our study also found that successful projects ensure that the hardware can be built using widely available materials and processes, which relates to compatibility.
	Product is available through multiple avenues	Confirmed
	Number of package dependencies	This is a software-specific metric that does not apply to hardware.
PROCESS	Project is active (bug fixes, documentation updates etc.)	Confirmed
	Project has goals and objectives along with an established process that members follow	Confirmed that successful projects have clear aims. However, this was not articulated in the form of goals and objectives specifically. Our study adds that good governance is also important.
	Bug reports are being addressed and fixed quickly	Confirmed
	How established is the software and how often are new features released	It is unclear what the authors mean by 'established.' In addition, releasing new features appears to be an attribute of software, as with hardware the implementation of new functionality requires the user to buy/make a new piece of hardware or accessories.
	How long has the project been active	Confirmed. Our study goes even further regarding this topic, finding that the sustainability of projects as well as any related business are paramount to success.
	Time between releases	Not confirmed, perhaps due to multiple releases being a software-specific attribute. However, our study did contain references to rapid development which could be related.

Category (adapted from Crowston et al. (2003))	Success measures (adapted from Crowston et al. (2003))	Comparison with the responses in the current study
DEVELOPERS	A number of developers contribute to the project	Confirmed
	A variety of developers from different projects and with different expertise contribute	While our study confirms that third party contributions i.e. contributions from people who have not participated before, as well as contributions from industry indicate success, we found that 'developers sharing similar expertise' also contributes to success, contrary to Crowston et al. (2003).
	Developers are satisfied	Confirmed
	Developers enjoy working on the project and with other project members	Our study did not identify specific references to enjoyment, however, we found related themes such as motivation, engagement, interest, group cohesion. We have grouped these terms in contributor satisfaction.
	Job opportunities and salary for developers	Financial reward for the contributors was not observed in our study. We found that raising funds for project activity is important, but it is unclear if that involves salary.
	Developers get a good reputation	Confirmed
USE	Software replaces competitive products	The OSH replacing existing market offerings was concluded in our study as well.
	Number of users of the product in addition to the developers	Confirmed – number of hardware users
	Number of downloads of product	Confirmed – number of downloads of documentation
	Number of views of information page	Number of views was confirmed in our study when it comes to views of the repository and documentation.

Category (adapted from Crowston et al. (2003))	Success measures (adapted from Crowston et al. (2003))	Comparison with the responses in the current study
RECOGNITION	Others recognise or refer to the project	Confirmed – paper citations
	Project attracts negative or positive attention	Partially confirmed. Attracting positive attention was confirmed in our study but negative attention was not referred to.
	New projects or spin-offs based on original project	Confirmed
INFLUENCE	Reuse of code or processes by other projects	Confirmed
PROJECT OUTPUT	Individual and organisational impacts in terms of economic and other implications	Individual impacts in terms of contributor and user satisfaction were confirmed. Organisation impacts such as funds raised, etc. were also confirmed. However, this is a vague wording from Crowston et al. (2003) so it is difficult to compare to.
	Movement from alpha to beta to stable	Indirectly confirmed – while alpha, beta and stable are software-related terms, we identified quick movement through the product development stages as a success characteristic, which could be considered equivalent.
	Project achieved identified goals	Implicitly confirmed. This was not explicitly mentioned in our study, however other references such as following clear aims and having certain intentions such as “replicated by as many people as is intended to reach” implies this.

When compared to the Core Infrastructure Initiative (n.d.) Free/Libre and Open Source Software (FLOSS) Best Practices Criteria which are used as part of a certification programme, we observed that apart from software-specific practices (code analysis, software security, etc.), most best practices they suggest are confirmed in the results of the here presented survey. Examples of best practices common to both OSS and OSH include having an open source license; having a defined governance model; having up-to-date documentation; having a high ‘bus factor’ (they suggest a minimum of 2 for their highest-level ‘Gold’); using distributed version control such as Git; and using an issue tracker for tracking different issues or bugs that may arise. This certification programme also provides some specific practices which relate to some of the more abstract characteristics identified. For example, they suggest that the project clearly identifies small tasks which could be undertaken by new or casual contributors. This relates to section 2.3.4.3.2, where attracting new contributors is discussed.

There were some differences between our results and Crowston et al. (2003), such as their finding of 'varied developers' as a success measure while we found 'developers sharing similar expertise'. This contradiction should be further investigated. Another difference was that Crowston et al. (2003) determined that negative attention towards the project could be beneficial, but we only found references to having a good reputation and positive attention in our study. Some differences include that the Core Infrastructure Initiative Best Practice Criteria also include certain practices which did not appear in the OSH survey. Examples of these include considering accessibility requirements for people with disabilities; requiring cryptographic two-factor authentication for changing the central repository or accessing sensitive data; defining key roles and responsibilities in a publicly shared document; linking tasks and people to those roles; and finally, having a community code of conduct.

Themes emerging from our study which were not identified by Crowston et al. (2003) include creating wider social impact (e.g. providing a product/tool that was previously inaccessible to certain groups of people); active attempts by the project to engage and grow the community around it; having good governance; and being sustainable (in terms of continuity of project and/or business). Furthermore, our study provides more detail and depth into certain themes. For example, we not only identified the importance placed on documentation quality, but also specific practices that affect it. It is, however, notable that while documentation Is important to success, in practice OSH participants "are not motivated to document" (Dai et al. 2020).

2.3.5.1.2 Comparison with NPD project management literature

When it comes to the iron triangle (time, cost, quality), our results refer to time in the sense of having rapid development, but no indication was given about completing a project 'on time'. Instead, we observed an underlying assumption in OSH product development that the project will be ongoing. Even if only a first version of the hardware will be developed in the project, the assumption is that eventually more iterations would follow. Project cost only appeared in the survey results in the context of having secured 'enough' funds for the project to continue performing its operations. Quality appeared in the survey results in terms of hardware and documentation, but also indirectly in the form of quality of the employed processes.

Four of the five dimensions of project success suggested by Shenhar and Dvir (2007) are confirmed in our study, namely: impact on the customer (the users), impact on the team (the contributors), business and direct success and preparation for the future. These are reported in section 2.3.4.1 on value creation. While the fifth dimension, efficiency, is not explicitly evident in our results, it could be linked to the project processes (reported in section 2.3.4.3). Our work adds depth to these dimensions by offering potential ways of measuring them in OSH projects.

In Table 4, we make a comparison with the seven characteristics of highly successful projects identified by Dvir and Shenhar (2011).

Table 4: Comparison of OSH project success characteristics with Dvir and Shenhar's (2011) project success characteristics.

Dvir and Shenhar (2011) project success characteristic	Comparison with the current study
Project creates competitive advantage and stakeholder value	This is confirmed in our study in section 2.3.4.1.
Long time taken to define project: create a strong vision, clear need and choosing the most suitable execution approach	The need for a clear vision is confirmed in section 2.3.4.3. Choosing a suitable execution approach was not identified in our study.
Project creates revolutionary project culture	This relates to the culture of the project compared to the overall culture of the firm, which is not the point of view adopted in our study.
Project has a highly qualified project leader who is supported by top management	This is not confirmed by our study as no references are made to having a leader, however, 'good governance' is a theme we identified which relates to this.
Project maximises use of existing knowledge, often in cooperation with outside organisations	Again, our study does not take the point of view of the firm. However, adopting external contributions was identified as a theme. Interestingly, our study finds that other projects reusing the designs of a project is a success characteristic, but not vice versa.
Project has integrated development teams which are adaptive and have quick problem-solving skills	While those skills are not identified explicitly, our study does confirm that a high-quality project team and good teamwork influences success, in section 2.3.4.3.
Project has teams with "strong sense of partnership and pride"	The value creation and project process categories in our results refer to contributor loyalty, satisfaction, motivation and interest as well as having effective collaboration, co-creation and teamwork within the project team. However, we do not observe explicit references to a sense of partnership and pride.

2.3.5.2 Open Source Hardware Project Success

This section presents a discussion of the themes uniquely important to OSH which emerged through the survey results. Section 2.3.5.2.1 discusses product openness; section 2.3.5.2.2 considers the contribution of process openness to success; section 2.3.5.2.3 expands on the ethical, societal, and political motivations in OSH projects; section 2.3.5.2.4 details the importance of business and sustainability, while section 2.3.5.2.5 addresses peer-reviewed publications.

2.3.5.2.1 Product openness contributes to success

The success characteristics identified in this study confirm the definition of OSH given by the Open Source Hardware Association (2018) as well as the four rights of OSH given by DIN SPEC 3105 which are essential to hardware being defined as OSH: that anyone can study, modify, make and distribute it. These definitions only refer to product openness. Transparency, full disclosure, and an OSH license would allow the four freedoms expressed in the definitions. However, there are aspects of projects beyond a license that are necessary in order to *exercise* the freedoms. For example, our results show that the hardware should be easily accessible for purchase from somewhere, which is not present in these.

The results of our study show that hardware sales by independent vendors different from the originator(s) can also be a sign of success. The existence of such vendors could indicate demand for the product. As such, other people see value in selling it, because it can generate a profit or other value.

2.3.5.2.2 Process openness contributes to success

Even though – according to the OSH definition (Open Source Hardware Association 2018) – only product openness is required for hardware to be termed open source, our results also identify having process openness to be a characteristic of successful OSH projects. This confirms all eight of the Open-o-Meter criteria identified by (Bonvoisin and Mies 2018), namely the presence and use of an OSH compatible license, design files, BoM, assembly instructions, original files, a version control system, a contribution guide and an issue tracking system. Our results also hint towards additional process openness criteria, e.g., presence of online forums and chats.

2.3.5.2.3 Ethical, societal and political motivations

The survey findings also confirm some already-known ethical, political and societal sentiments which often underpin peoples' motivations for participating in and advocating for, open source development. We observe responses mentioning that projects following an open source 'path' might not necessarily be the cheapest – i.e., financial sacrifices may be made for the 'higher good' of remaining open. Even though it is unclear in the data how this may manifest, it underpins a sentiment of making sacrifices if needed to maintain open source status.

The democratisation of knowledge was a recurrent theme in the responses. This indicates a sentiment of sharing information and knowledge with others without discrimination, i.e., the inherently political notion of equal rights for access to knowledge.

Multiple survey responses made references of wider social impact as being a characteristic of project success, in that the project creates value to science and society. Some quotes from the survey include: "giv[es] access to tools usually out of reach to the less fortunate", "enables learning", "helps democratise knowledge", "citizen science movement", etc. We observed a notion of accountability on OSH projects to be of value to human lives and the evolution of society. The respondents believe that for these projects to be successful, they must somehow contribute to this 'higher cause' of bringing about positive scientific and social change. Examples mentioned include allowing knowledge to be democratised and disseminated to all those who need it, without discrimination; enabling access to tools that were previously not available to certain communities of people; and more generally contributing to the development of science and technology.

These factors point to one of the core principles of open source development, which is accessibility. While Balka et al. (2014) define accessibility in terms of a person being able to participate in the product development process, in our study we found that accessibility can take additional meanings. Our data gave examples of accessibility such as: access to the original 'source' of the product; access to materials needed to make the product; access to an assembled or do-it-yourself (DIY) kit of the hardware; but also access to a *knowledge* or *capability* – notions whose value to individuals and society are less tangible or measurable.

Democratisation of knowledge

When referring to democratising knowledge, we denote the spreading of knowledge amongst *all* people, without discrimination, not just limiting it to those who have certain privileges. A cornerstone of the democratisation of knowledge is therefore *access to information*. OSH–- and in general the open source movement – are inherently contributing to the democratisation of knowledge by their nature itself – the blueprints of the products are openly shared, sometimes along with the design process too. Even projects on the lower end of the 'openness scale' (see Open-o-Meter by Bonvoisin and Mies 2018), still provide a certain contribution to the democratisation of knowledge, in comparison to closed source hardware developed through conventional product development. One might argue that the technical features of some closed source hardware are publicly shared if it is patented. However, patents describe little beyond the working principle(s) and rarely provide details on materials, specific components, dimensions, or manufacture. While patents might provide some access to knowledge, they prohibit using that knowledge in a meaningful way without obtaining a proprietary license from the patent holder.

Survey respondents believe that a successful project might be characterised by its contribution to the democratisation of knowledge. From this, it is possible to hypothesise that the extent of its contribution to the democratisation of knowledge, relates to the extent of the project's success, and is worthy of future study.

2.3.5.2.4 Business and Sustainability

Conducting business activity was identified as a characteristic of successful OSH projects in this study. Commercial success validates the product itself, proving the value of the hardware, as well as the viability of OSH for conducting a profitable business.

The sustainability of both the project and any associated business was a theme that emerged from the survey responses. Sustainability in this context means the ability of the project to continue conducting its operations and activities “beyond the lifetime of the creator”. Sustainability is influenced by how much knowledge is available; how well that knowledge is shared; the ‘bus factor’; and funds. Funding emerged as an issue because it influences how much a project can do and how well it could sustain itself in the future.

Scholars have proposed creating sustainable value in OSH (Moritz et al. 2017). Research has also proposed using OSH as a business model for companies (Li and Seering 2019), with the option of moving away from if they wanted, rather than basing the company around the OSH product(s). They advise companies using OSH to make the OSH development model more sustainable such as: develop a strong brand; have fast innovation with the assistance of the community; and use the knowledge and experience gained through what they call the ‘open source stage’; and then produce closed source associated hardware and/or extensions. The latter, however, may be perceived by some to be against the open source ethos and this has been specifically pointed out in the survey responses of the present study. Companies who have done this have indeed attracted criticism. For example, MakerBot who released its first version as OSH, and was itself based on the OSH Rep Rap 3D printer, received such criticism (Hall 2016; Brown 2012). Pearce (2017) does not consider OSH as a singular business model, and instead outlines a variety of business models that could be used in an OSH project, depending on the audience e.g., selling self-assembly kits of the hardware, selling pre-assembled hardware units, selling a service based on the hardware.

Our findings show that conducting business and being sustainable over time are important factors by which the success of a project can be evaluated, and thus relevant metrics and indicators could be used to assess them.

2.3.5.2.5 Peer-reviewed publications

Peer-reviewed publications are especially important in the academic OSH community as the number of which is a metric that influences an academic’s career, and thereby creates value to academic contributors. It also gives a certain prestige and officiality to the associated hardware if an extended form of its documentation is published in an academic journal. A few OSH-focused journals exist which accept submissions for OSH designs.

2.3.5.3 Limitations and future work

This study provides insights into characteristics of successful OSH projects, some preliminary best practices and metrics for measuring success. Further studies could investigate creating tailored best practice suggestions for OSH projects based on their unique contextual factors, such as the type of product being developed. These could then form the basis of a guideline for helping OSH projects steer themselves towards success and could also inform the development of standards.

Dashboards, graphical user interfaces used for giving visualisations of key performance indicators for projects, are increasingly used on project hosting websites such as GitHub to give visitors and developers at-a-glance information about the status of each project. Dashboards may help potential contributors select projects that they are interested in. The metrics we identify could be implemented on such dashboards on online OSH project repositories, and they can then be used in conjunction with suggestions for ways to improve the scores on those metrics. In this way, the outcomes from OSH projects could be improved.

The existing data set and insights from this study could also be further analysed to produce a draft framework for the relationships between value creation, quality of output and project processes observed in successful OSH projects. Conversely, this framework could then also be used as a basis for analysing how and why OSH projects fail.

Adaptive project management is a method that involves adapting the style of managing the project based on certain variables (Shenhar and Dvir 2007). While we expect adaptive project management to be applicable to OSH development, further studies could investigate the relevant variables.

While our results provide a step forward in characterising success in OSH, it is important to highlight its limitations. The first of those relates to the sample used. Given the exploratory nature of the study, we used a qualitative approach with a sample of 30 individuals. While this approach enabled us to use rich insights for uncovering relevant themes in defining success and to reach saturation, we cannot claim the sample is representative of the entire population of OSH practitioners. Moreover, while we distributed the survey in person and online to practitioners, we cannot completely exclude bias due to self-selection. It is also possible that the dataset is biased towards a certain group of OSH practitioners, for instance, those who only participate in projects which develop a certain type of hardware e.g., electronics. To mitigate the sampling limitations, future studies could collect a larger number of respondents through a wider range of platforms, as well as capture more information on the backgrounds of those respondents. The latter could also aid in discovering what success characteristics, practices and metrics are related to specific types of OSH projects.

Second, the sample does not allow us to draw conclusions on the relative importance of each of the themes identified, nor were any metrics used to objectively evaluate success in projects. Thirdly, while we focused on practitioners, we do not investigate the role or experience in OSH projects of the respondents (e.g., project initiators, contributors, end-users, etc). Future studies could identify the relative importance of the success characteristics in relation to OSH participants' roles and levels of expertise. Furthermore, as described in section 2.3.3.3, the answers to the survey questions were treated as one dataset. Further studies could research factors, practices and metrics for success individually in more depth, along with the relationships between them. Lastly, a quantitative research study measuring success in OSH projects could test the validity of our conclusions.

Despite these limitations, we believe that this study can provide useful insights both to OSH practitioners and scholars interested in understanding how to support the success of OSH projects. We also hope that this study will foster the discussion on the specific characteristics of the OSH community.

2.3.6 Conclusions

This study is a first step in characterising OSH project success and identifying success characteristics that are uniquely important to OSH development from the point of view of practitioners. Using thematic analysis on a dataset of written answers to open-ended survey questions given by OSH practitioners, we outline various characteristics of successful OSH projects through three high-level themes. Those themes are “successful projects create value”, “successful OSH projects create high-quality outputs” and “successful projects have effective processes”.

We also suggest some practices for promoting success and metrics for measuring it which were indicated by the dataset. Furthermore, we contrast OSH success with success in OSS and NPD project management literature. This allowed us to present success characteristics that relate to OSH projects specifically. Examples include having process openness which brings about wider social impact; providing access to new knowledge; giving access to a tool/product/device previously unavailable to certain groups of people; and having business and project sustainability over time.

The insights from this study answered the research questions “What characteristics and practices are present in successful OSH projects?” (RQ1) and “What metrics can be used to measure success in OSH projects?” (RQ2) and fulfilled the objectives of understanding success in OSH projects and identifying success characteristics which are uniquely important to OSH development. Consequently, the results have implications for practitioners when planning and managing an OSH project, and provide a basis for future work for researchers studying factors leading to OSH success. This study can also help inform the creation of a success guideline for OSH projects.

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2.4 Epilogue

Paper A presented the first empirical study in this thesis. This work provides a general understanding of the characterisation of successful OSHD projects from the perspective of practitioners.

The study presented in paper A answered all the intended research questions. Concerning ***RQ1*** *"What characteristics and practices are present in successful OSH projects?"* three top-level characteristics were identified which were: successful OSH projects create value; successful OSHD projects create high-quality outputs; and successful OSHD projects have effective processes. Each of these top-level characteristics contained a variety of other 'sub-characteristics' and relevant practices. In terms of ***RQ2*** *"What metrics can be used to measure success in OSHD projects?"* 101 metrics, which relate to the identified characteristics, were suggested for measuring success in OSHD projects. For ***RQ3*** *"Does success look different in OSHD projects than in OSSD?"* it was found that project success appears to be quite similar in OSHD and OSSD projects, with a few exceptions which were described. Lastly, for ***RQ4*** *"How does success in OSHD projects compare to success in NPD project management?"* some similarity was found, along with various differences which were discussed.

2.4.1 Connection to the next section

A logical conclusion which could be drawn from the study presented in paper A is that different success characteristics, practices and metrics may be of varying importance to different projects. For example, the number of research paper citations is likely to be highly relevant to researchers and academics as a success metric but could be less so for those who are not researchers or scientists and develop OSH as a hobby. Therefore, as mentioned in section 2.3.5.3, future studies could attempt to create tailored best practice advice for projects based on their unique context. To do this, it would first be required to understand the breadth of variety in OSH projects, in order to tailor the best practice advice. This leads to the research question "what are the different types of OSH projects?" On this note, section 3 presents a typology study which attempts to identify different types of OSH projects. These types could then be used to test whether they can help to inform guidelines which ultimately aim to improve practice and successful outcomes in OSHD projects, which is addressed in section 4. Section 4 also looks further into one of the identified success characteristics, hardware replicability.

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Section 3. A typology of OSHD projects

Classification and typologies are important because, among other things, they can help provide descriptive and explanatory frameworks for ideas. In this section, a research study is presented which involves the creation of a typology of OSHD projects. Section 3.1 provides an introduction to the study offering the rationale for creating a typology, the research gap, questions and the overall structure of the remainder of this section.

3.1 Introduction

Some project management academics contend that all projects are fundamentally similar, and this can be summarised by the axiom "a project is a project is a project" (Pinto and Covin 1989). Other academics, such as Shenhar and Dvir (1996), argue that in reality, projects exhibit significant differences. They argue that capturing these differences in the form of a typology can inform project management practice and their effect on project success. They also state that such a typology can also help develop theory, for example by deepening the understanding of projects and the relationships between their characteristics.

Adopting this point of view of Shenhar and Dvir, (1996), this section presents a research study into developing a typology of OSHD projects. This typology intends to capture some of the variation that exists across different OSHD projects by placing them into types, with similar projects placed together in the same type. The ambition is that the identification of these project types would aid the understanding of the OSHD field from a theoretical research perspective, by, according to Kwasnik (1992), providing a descriptive and possibly also explanatory framework for ideas.

In new topic areas of research, case studies are often an appropriate way of expanding the knowledge of the topic (Eisenhardt 1989). Some case studies have been presented in the recent OSHD literature (Moritz et al. 2017; Bonvoisin, Mies, Thomas, et al. 2017; Li et al. 2019; Moritz et al. 2019). A few quantitative studies have also emerged (Jaspers 2014; Bonvoisin et al. 2018; Bonvoisin, Mies, Boujut, et al. 2017). In this study, the author employed a mixed-methods research methodology, whereby qualitative data about OSHD projects collected manually by observing their online presence are analysed by employing quantitative methods (Phi correlations and hierarchical cluster analysis).

This section is organised as follows: section 3.1.1 outlines in general terms why a typology of OSHD projects is needed; section 3.1.2 summarises the research gap which highlights the originality and positioning of this study within the literature; section 3.1.3 explicates the research aim and research questions upon which this study is based; and section 3.1.4 outlines the structure of this section.

3.1.1 The need for a typology of OSHD projects

In the previous study presented in section 2, the researcher identified several characteristics of successful OSHD projects, along with multiple best practices and success metrics. It is hypothesised that the relevance of these to each project varies based on the characteristics of the project. To illustrate this point, let us take the following example: the study in section 2 identified that selling products and generating lots of revenue is an indicator of project success. However, this is likely to be the case in projects which intend to create a product to be sold, but may be less relevant to those which intend to make a prototype or a product just for their own use with no intention of manufacturing with the intention of sales. This alludes to the fact that there are different types of OSHD projects, which would then influence what kind of best practice advice could be given to them.

It is hypothesised that there is a large variety of OSHD projects. This hypothesis is founded on the previous study in section 2. The variation across projects in the field of OSHD has not been previously studied in the literature with a view to categorise projects. The author poses that it is important to do so because it could help with:

- The advancement of research understanding of the field of OSH
- The formation of a foundation for adapting processes and tools to projects
- The development of tailored guidance to projects, such as success indicators, metrics and best practices, based on their unique context and features.

The last two bullet points are in line with recommendations from Crawford, Hobbs and Turner (2002), who discuss the suitability of classifications for projects.

To investigate the variation across different OSHD projects, we can look at their characteristics. Similarities and differences across project characteristics can then help us classify the projects into groups. These groups can then be used to describe the variation across OSHD projects and assist with tailoring advice given to the project in terms of best practices for success, and metrics and indicators for measuring progress. We refer to the outcome of this classification as a 'typology' of OSHD projects. This terminology is further explained in the later sections.

3.1.2 Research gap

At the time of writing, there are no theoretically or empirically-based classification systems for OSHD projects. To create one, the most important characteristics of OSHD projects must first be identified, because these will determine the project types.

3.1.3 Research questions

This study asks the overarching research question: **what is the breadth of variety of OSHD projects?** With this top-level question as a foundation, we formulate the following line of inquiry:

RQ1: What are the main characteristics of OSHD projects?

RQ2: What project 'types' can be identified based on the similarities and differences between the characteristics?

RQ3: What insights can be drawn from these project types?

Section 4 will investigate the possibility of using this typology to inform practice advice, which could help improve practice and successful outcomes in OSHD projects.

3.1.4 Section structure

Further in this section, section 3.2 describes the research approach employed in this study. Sections 3.3-3.6 describe the four main steps taken to develop a typology for OSHD projects, and address RQ1. Section 3.7 describes the final typology – the three types of OSHD projects resulting from rigorous data collection and analysis, addressing RQ2. Section 3.8 offers a brief discussion of the findings of this study, addressing RQ3. Section 3.9 ends with a reflection on the conclusions and limitations of this study.

3.2 Research Approach

This section addresses the research approach employed in this study. Section 3.2.1 presents the unit of analysis, while section 3.2.2 justifies the usage of a typological approach.

3.2.1 Unit of analysis

To determine the unit of analysis, we turn to the OSH definition, which states that OSH 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 2018)". It is clear that the term OSH refers to the hardware **artefact.**

The authors term the **process** by which OSH is developed 'OSHD'. OSH development is carried out by what the author calls 'OSHD projects', which refers to the context in which the OSH is being developed.

The Project Management Institute (PMI), a global association for project management professionals defines a project as "a **temporary** endeavour undertaken to create a **unique** product, service or result"[26]. The project management literature often considers projects as only taking place in an organisational setting, i.e. a company. In addition, they are contextualised as different from operations:

> *"Operations involve repetitive, ongoing activities, such as manufacturing, service and production, whereas projects involve unique, one-time initiatives, such as launching new products, new organisations or new ventures, improving existing products and investing in the compan"s infrastructure."*
>
> *- Shenhar and Dvir (2007).*

When considering OSHD, we focus on the overall endeavour of designing and developing a specific, unique product (the OSH). However, the PMI definition of a project is limiting since it implies that this endeavour is temporary. Within OSHD projects where the formality of organisation (and perhaps by extension the project management) is often low (Bonvoisin, Mies, Thomas, et al. 2017), it is hard to tell when a project starts and ends. Take for example the case of a group of people designing, developing and then selling a product, but in the meantime continue improving it to develop and sell new versions. How can we tell at what point in time the first project of developing the first version started and finished, and when the second project started? How can we recognise if there were any differences in the goals and objectives of each project without formal documentation?

In this research, we use the term '**OSHD project**' to refer to the endeavour of design and development of OSH but ignore this limitation of temporality in the definition of 'project' by PMI. The terms 'OSH project' and 'OSH development project' are also often

[26] https://www.pmi.org/about/learn-about-pmi/what-is-project-management

used in the OSHD literature. Interestingly, the author has not come across literature which explicitly defines these terms.

In OSHD projects where organisation and management are not very formal, deadlines and timescales may not be used, and the design may be continually improved ending up in the creation of multiple variants. Cases where a hardware is continually improved upon to develop multiple variants have been observed, for example, the Otto DIY robot. In such cases, it is difficult to say which activities constitute 'the project', especially when there are multiple groups of people who are concurrently developing variants of the same model. It is difficult to draw the line as to where one project becomes many projects, so for simplicity, in a case like this, we would consider a specific Otto DIY robot variant to be a single project. To make this even simpler, a database will be used which provides a list of projects, which provides a standardisation of what is considered to be a project.

3.2.2 Classification and typology

Classification essentially is the process by which cases are systematically arranged into groups (McQuitty 1987). Classification helps to make "things more manageable" (Crawford et al. 2002). Bowker & Star (2000) call classification "the scaffolding of information infrastructures" and pose that "to classify is human", hinting that it is deeply rooted in human nature. According to Kwasnik (1992), classification outcomes "provide a descriptive and explanatory framework for ideas and a structure for the relationships among the ideas". They also facilitate comparison between different cases (Durand and Paolella 2013).

There are a variety of terms being used to refer to the process of putting things into categories. Most frequently, we hear terms like 'classification' and 'categorisation'. In this thesis, the author tends to use the term 'classification'. In practice, the terms 'classification' and 'categorisation' are often used interchangeably, and we often even say 'classification' into 'categories'. Even though there is an underlying assumption that the terms 'classification' and 'categorisation' refer to the same process, strictly speaking, these two terms have different definitions in the literature (Jacob 1991). For this study, the author does not delve deep into the minutiae of the differences between these definitions. The term 'classification' is simply used to refer to the process of placing OSHD projects into categories based on how similar (or different) they are to each other.

The term classification has a variety of meanings in the literature (Marradi 1990). In this study, we ascribe the following meaning to the classification process, given by Marradi (1990):

"[Classification is] an operation whereby the objects or events of a given set are grouped into two or more subsets according to the perceived similarities of their states on one or (more frequently) several properties".

Additionally, Marradi (1990) sheds light on the fact that the classification process can also result in different outcomes, such as a 'classification scheme', a 'typology', or a 'taxonomy'. We refer to the outcome of the classification process carried out in this study as a 'typology'. Since the term 'typology' is used, the term 'types' is therefore used to refer to the categories of OSHD projects in the typology.

Typology is an analytical approach which helps capture and organise the distinct characteristics of a research phenomenon. Its value can be seen through its application in various fields in order to conceptualise research phenomena. For instance: child psychology - Mandara (2003); business management - Yrjölä et al. (2021); project management - Lehmann (2016) and Shenhar and Dvir (1996). The typological approach is a mixed-methods one, involving the organisation of cases into types based on their similarities and dissimilarities. It is an intermediary between extreme variable-centred and extreme case-centred approaches (Mandara 2003). Variable-centred approaches are highly–quantitative and often result in conclusions such as "variable X is positively/negatively correlated to variable Y", while case-centred approaches involve qualitative methods and a rich characterisation of specific cases, but the results are limited in terms of generalisability (Mandara 2003).

According to Marradi (1990), the term typology is used when the outcome of the classification process involves the consideration of multiple aspects which differentiate the concept in question – the concept being OSHD projects in this study. By contrast, the author does not use the term classification scheme because it applies when only one differentiating aspect is considered for the classification (Marradi 1990). Similar to typology, the term taxonomy as the outcome of the classification process is used also when several aspects which differentiate the concept in question are considered. However, it is specifically used to refer to the output of *a series* of classifications (Marradi 1990), which is out of the scope of this study.

3.3 Step 1: Identification and collection of a sample of OSHD projects

Firstly, it is important to identify and collect a sample of OSHD projects to analyse in order to create the typology. In this section, section 3.3.1 outlines how a sample source was selected, section 3.3.2 describes the selected database in detail, and section 3.3.3 shows how a list of projects was extracted from the sample source.

3.3.1 Sample source selection

The analysed projects must be indeed open source, to ensure validity. A good way to do that would be to analyse projects that comply with the widely-accepted OSH definition by OSHWA (2018), a well-established non-profit organisation which advocates for OSH[27]. This definition is widely accepted (Bonvoisin et al. 2020; Bonvoisin et al. 2021), and originates from the seminal work of Balka (2011) which is described later in section 3.4.1. the OSH definition by OSHWA is heavily used in the literature for defining the meaning of OSH (e.g., Bowser et al. (2021); Maia Chagas (2018); Moritz et al. (2017); Kim and Hong (2018) to name a few) and it is also used in standardisation efforts (Bonvoisin et al. 2020).

Eight possible sources of samples of OSHD projects were identified, which could be used in this research study. They are displayed in Table 5, along with a description of each and their pros and cons.

Table 5: Descriptions of the possible sample sources.

Sample Source	Description
Wikipedia list of OSHD projects[28]	A Wiki page containing a list of OSHD projects separated by categories. Projects are placed in categories with links to the Wikipedia pages of each project. The fact that Wikipedia pages exist for these projects indicates a certain level of maturity. The list is arbitrary, with no indication of selection criteria. In addition, the 'openness' criteria which are used to deem the projects as OSHD are not stated.
List of projects by Joshua Pearce[29]	Created by Joshua Pearce[30], a prominent academic engineer who is a researcher in the field of OSH. It is a neat list of open source projects for people to use in order to save money, that he published as part of his book titled "Create, Share, and Save Money Using Open-Source Projects" (Pearce 2020). Projects are placed into categories with links to each project. Not all are OSHD, some are OSSD. OSHD projects are mainly DIY. A lot of projects, with many not having a description. The 'openness' criteria which are used to deem the projects as OSHD are not stated.

[27] https://www.oshwa.org/about/
[28] https://en.wikipedia.org/wiki/List_of_open-source_hardware_projects
[29] https://www.appropedia.org/Create,_Share,_and_Save_Money_Using_Open-Source_Projects
[30] https://en.wikipedia.org/wiki/Joshua_Pearce

Sample Source	Description
Open Know-How (OKH) search engine[31]	The OKH Specification developed by the Internet of Production Alliance is an attempt to "improve the openness of know-how for making hardware"(Wardeh 2022). The specification recommends the addition of a 'manifest' to OSHD project repository home pages, a file which contains specific project information outlined in the specification. This manifest enables the indexing of that OSH into the OKH search engine, which helps enhance the 'discoverability' of OSHD projects by interested people. While the presence of a manifest within the repository of a project indicates that the project identifies as OSH, it does not necessarily articulate by which 'openness' criteria the project identifies as open source. Another issue with this database is that it does not provide a way to download the list of projects found there.
Library of Open Source Hardware (LOSH)	A search engine similar to the one by OKH, created by the OPENNEXT project[32]. Since the author also worked on the OPENNEXT project, she spoke to one of the LOSH creators who indicated that most of the projects on the LOSH database are the same as the OKH search engine, since they are 'discovered' through the manifests. While the LOSH database allows for downloads of the projects listed, it again suffers from unclear 'openness' criteria.
Wikifactory[33]	Wikifactory is a "manufacturing ecosystem" (Wikifactory: Overview | LinkedIn n.d.) where people can share designs, create prototypes and manufacture their products online. It also acts as a project repository, hosting a multitude of OSHD projects. However, it is not possible to extract a list of projects from their database, nor are there indications as to whether the projects are open source or not.
GitHub[34] **& GitLab**[35]	GitHub and GitLab are websites which are both very often used for hosting OSHD projects. While they are primarily used for software development projects, OSHD projects can be found there too. However, it is very difficult to identify OSHD projects on those websites as they are not clearly and consistently labelled as such. Therefore, it is not possible to download a list of the OSHD projects stored there due to not only the issue of identifying them but also the fact that code needs to be written to query the databases to export this information. There are scripts which can scrape these databases to extract information (see for example Scrapy[36]), however, these are not straightforward to use specifically for scraping OSHD projects and require high-level coding skills.

[31] https://search.openknowhow.org/
[32] https://opennext.eu/
[33] https://wikifactory.com/
[34] https://github.com/
[35] https://about.gitlab.com/
[36] https://github.com/scrapy/scrapy

Sample Source	Description
OSHWA database of certified projects[37]	OSHWA runs a certification programme which enables creators (individuals or organisations) to indicate that the products they produce meet a "uniform and well-defined standard for open-source compliance"[38]. The projects listed on this database have been self-certified as open source according to the OSHWA definition (Open Source Hardware Association 2018). It is possible to download a list of the projects certified, using a 'plug-and-play' script[39]. This script allows the automatic scraping of this database to download a list of all the certified projects along with some information about them (such as country of certification, project description, licence type, etc.).

Four criteria were considered in order to select the most suitable sample source to be used for data collection. These criteria along with the rationale for considering them are shown in Table 6.

Table 6: Criteria and rationale for assessing potential OSHD project sample sources.

Criteria	Rationale
Projects are open source based on clearly articulated criteria	In this study the author focuses specifically on OSH, therefore the criteria by which the projects in the sample source are deemed as OSHD must be stated.
Projects listed develop hardware specifically	Again, in this study, the author focuses on OSH. Therefore, it is important that the sample source specifically lists hardware and not software projects. Listing both is not a problem when there is a clear way to filter specifically for OSHD projects.
Ability to download a list of projects to be analysed	To have a list of projects to be analysed for this study, it is essential to be able to extract a list of projects to be analysed. It is possible to create a list of projects manually, but this is too time-consuming, so it is preferred to be able to have an automatic way of downloading a list of projects.
Variety of OSHD product types	This study aims to create a typology of OSHD projects. This should therefore capture the variety of projects that exist. As such, the source of OSHD projects to be analysed must not apply a specific bias to the projects, i.e. listing projects only medical projects, or only DIY projects, etc.

Table 7 shows an evaluation of the sample sources described in Table 5. The OSHWA database was the only sample source which fulfilled all four criteria. All the sample sources were potentially good candidates to be used for obtaining a list of OSHD projects, however, they all suffered from the fact that manual work needs to be done to ensure that each project identified from those sources complies with the OSHWA

[37] https://certification.oshwa.org/list.html
[38] https://certification.oshwa.org/requirements.html
[39] https://github.com/stevenabadie/oshdata-tools

definition, which we are using as a foundation for this research. Additionally, something which was not a selection criterion but was an added benefit was the fact that the OSHWA database contains certain information about the listed projects which allows us to perform some descriptive statistics, e.g., number of projects by country, by creator etc. As such, the OSHWA database is a natural choice for identifying a list of OSHD projects.

Table 7: Evaluation of sample sources based on selection criteria.

Sample source selection criteria	**Wikipedia**	**Joshua Pearce list**	**OKH**	**LOSH**	**Wikifactory**	**GitHub**	**GitLab**	**OSHWA database**
Projects are open source based on clearly articulated criteria	✗	✗	✗	✗	✗	✗	✗	✓
Projects listed develop hardware specifically	✓	✗	✓	✓	✓	✗	✗	✓
Ability to download a list of projects to be analysed	✓	✓	✗	✓	✗	✗	✗	✓
Variety of OSHD product types	✓	✗	✓	✓	✓	✓	✓	✓

3.3.2 Description of OSHWA database as a sample source

The following list provides a summary of the OSHWA certification requirements:

1. The hardware created complies with the OSHWA definition[40]
2. All creator's contributions and parts within their control in an OSH using the certification mark are shared as open source
3. Third-party proprietary components used in the OSH should be distinguished and have fully accessible and shareable datasheets
4. The creator must self-certify each project into the certification programme and register each unique product bearing the certification mark

The projects, which are self-certified by the creators, along with information about them, are available to view through an online database[41]. The OSHWA-certified projects database contains 17 information items (such as 'project type', certification country, certification data and hardware and software licenses used) on each project. These are collected when someone fills in the 'certify a project' form on the OSHWA website[42].

[40] https://www.oshwa.org/definition/
[41] https://certification.oshwa.org/list.html
[42] https://application.oshwa.org/apply

They are listed in Table 8, along with a reference number (for the purposes of this study) and a description.

Table 8: Project information collected and displayed by OSHWA on their website.

Ref	Information	Description
1	Project name	The name of the project.
2	Creator	The name of the creator of the project. OSHWA limits this to the name or 'individual', a 'company' or 'organisation'.
3	Public contact email address	An email address which is publicly visible on the project's OSHWA certification page, which can be used to contact the project.
4	Description	A short description of the project of up to 500 characters
5	OSHWA UID	A unique identifier for the project generated by OSHWA. Consists of two alphabetic characters which represent the country of certification, followed by six numeric characters. Starting from 000001 going up.
6	Version	The version number of the hardware.
7	Project website	A URL to the project's website.
8	Previous versions	A link to the OSHWA certification page of any previous version(s) of the hardware.
9	Date of certification	The date the project was certified.
10	Country	The country of the contact information given by the creator.
11	Hardware license	The name of the license used for the hardware elements of the project
12	Software license	The name of the license used for the software elements of the project
13	Documentation license	The name of the license used for the documentation of the project
14	Documentation link	A link to the digital repository of the project's documentation
15	Project types	A list of 17 options, with one of the 17 being 'other'. One can select as many 'project types' as they want. 1. 3D printing 2. Agriculture 3. Arts 4. Education 5. Electronics 6. Enclosure 7. Environmental 8. Home Connection 9. IOT 10. Manufacturing 11. Robotics 12. Science 13. Sound 14. Space 15. Tool 16. Wearables 17. Other

16	Project keywords	A user-inputted list of keywords. No limitations on what the keywords can be.
17	Citations	URL(s) to projects which are used in the development of the certified project.

The OSHWA-certified projects database displays the certified projects in a list. One can click on each project to see expanded information on it. This is the 'project page'. Figure 8 shows the project page for the project named 0XCB 1337 which we display here as an example. The page is annotated in green rectangles with the reference numbers from Table 8.

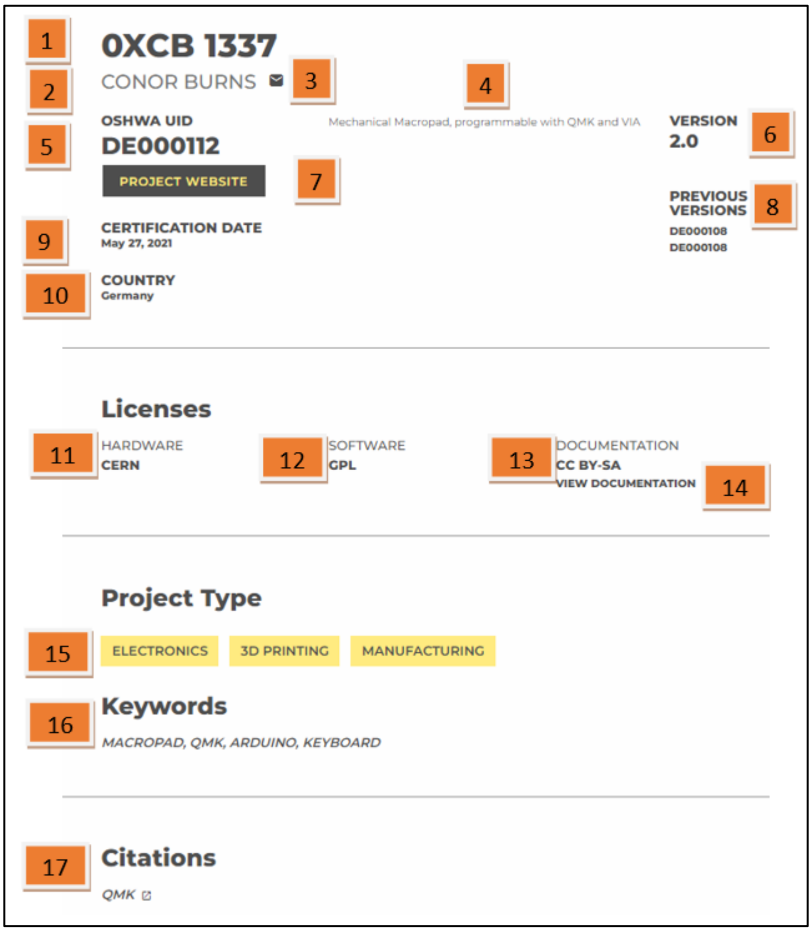

Figure 8: The OSHWA page for the project named 0XCB 1337 by creator Conor Burns, annotated with numbers in green rectangles, corresponding to the references in Table 8.

It is important to note that the OSHWA database is not without limitations as a sample source. For example, it may be limited in the number and variety of projects it lists, due to the requirement that an OSHD practitioner self-certifies the project. This has as a prerequisite that the practitioner already knows about the database, meaning that there are likely to be many OSHD projects which are not listed due to the practitioners lack of knowledge about database. Further, the practitioner must have seen value in making the effort to self-certify their project. As such, this may mean that even more projects are not listed as the practitioners may have not felt that OSHWA certification was worth the effort.

3.3.3 Sample collection

The open-source Python script, oshwa_scrape.py, developed by OSHdata[43] scrapes the OSHWA database to create a .csv file with all the projects certified and all information logged about them. That list can then be formatted as a spreadsheet for the information to be sorted an analysed.

The script was run on 24 March 2021 and 1527 entries (i.e., OSHD projects) were logged. The data collected by the script includes: a unique identifier reference for each entry, certification date, project name, website, creator, country, project type(s), description, version, hardware license, software license, documentation license and documentation link (as per Table 8).

271 unique creators were identified, after screening for duplicates, as sometimes the same creator would be listed under two very similar names. The creator with the most certified projects was Adafruit Industries LLC, with 444 projects, 443 listed under the name 'Adafruit Industries LLC' and one listed under 'Adafruit'. They were closely followed by SparkFun Electronics, which certified 402 projects. All the remaining creators certified less than 100 projects. Notably, 194 creators had certified only 1 project.

Most projects were based in the United States of America. The geographical distribution of projects is displayed in Figure 9.

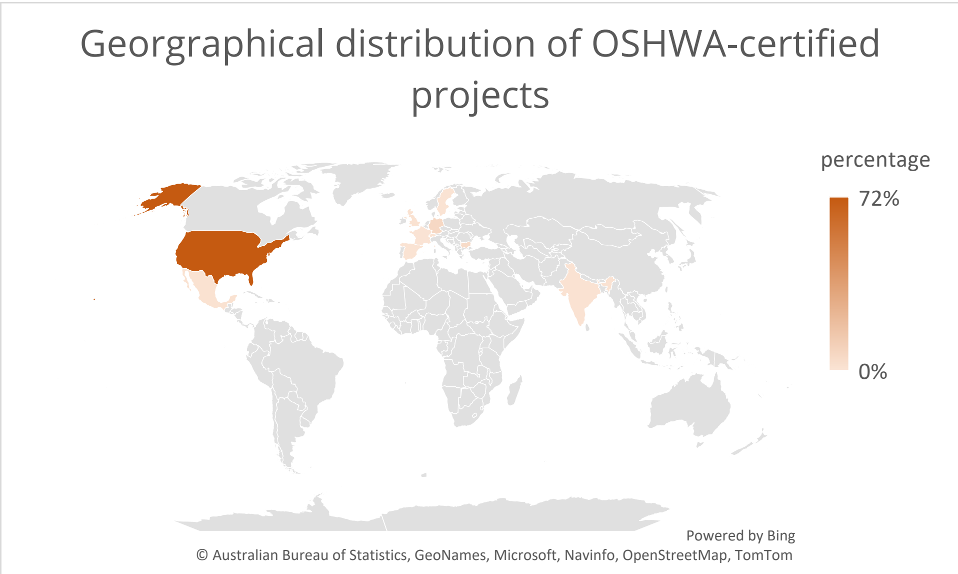

Figure 9: Geographical distribution of projects in the OSHWA database on 24 March 2021.

To analyse the data, the projects were first sorted by creator in alphabetical order. The list of creators included both company names and individual's names. Only one project was analysed from each creator, chosen at random. This was an arbitrary way of sorting the dataset, meaning the projects should be random (as opposed to sorting by product name which may mean that products with similar names who perhaps fulfil similar purposes are over-represented). Then, the links given in the data were followed to

[43] https://github.com/OSHdata/oshdata-tools

obtain information on the creator and the products, particularly whether they are an organisation or an individual, if they are selling the product or not (business vs hobbyist) and what goals they have, if any are publicly listed. If the webpages did not provide enough information, other links were followed within them and searches were also performed on the organisation/individual and the product(s) using Google.
After every 5 creators' data was collected, we revisited the data collected to see if any themes have emerged. The next section describes the data collection step in more detail.

3.4 Step 2: Identification of the differentiating characteristics of OSHD projects

To create a typology of OSHD projects, we need to understand what characteristics differentiate the projects from each other. There is a wide range of characteristics which could characterise these projects, such as country of origin, whether the project team consists of one person or multiple, whether the project team is co-located or not, the stage of the product development, etc. These are reviewed in section 3.4.1. The author identified these through a literature review and a scan of OSHD project hosting or listing databases. It must be noted however that currently there are no possible automated methods for collecting all this information since it is scattered across the internet on various websites in a non-structured way, so the list of characteristics identified here is limited to what is available to the author's knowledge. The author also chose to consult three OSHD experts, which she interviewed to extract their opinions on possible characteristics which differentiate OSHD projects, along with their impressions about what types of projects might be out there. This is described in section 3.4.2.

3.4.1 How are OSHD projects currently characterised?

Bonvoisin et al. (2017) identify what they call two main OSHD project 'archetypes'. An archetype by definition is "the original pattern or model of which all things of the same type re representations or copies" (*Archetype Definition & Meaning - Merriam-Webster* 2022). The 'archetypes' Bonvoisin et al. (2017) identified are: the 'isolated innovator' and the 'development community'. The former is a project led by a single person and in which little to no community contributions are incorporated, while the latter involves product development to which a community of people contributes. These are the two ends of the spectrum, there could be different levels of community involvement in the projects lying in-between. These 'archetypes' show interesting potential to be used in a classification system since they could potentially influence the types of working practices which could be helpful to the project. However, it must be noted that it is unclear how these 'archetypes' were derived and that they seem to refer to the human resources of a project only – perhaps this is a limited view of OSHD projects, and more characteristics could be considered for classifying projects.

To get inspiration for potential OSHD project characteristics to be used for classification, we investigate what OSHD project characteristics different online databases record when listing OSHD projects. Databases which list OSHD projects record several different characteristics of the projects. For example, OSHWA has a list of all the projects it has certified[44] and can be filtered by country, what they call 'project type' – which would perhaps be more accurately named as product type – (e.g. electronics, manufacturing, wearables, etc.) and associated licence type(s) (CERN, Apache, etc.). The Open Hardware Observatory (OHO)[45] Project Directory records the listed OSHD projects' product

[44] https://certification.oshwa.org/list.html
[45] https://en.oho.wiki/wiki/Home

category (arts & entertainment, toys & games, home & garden, and, confusingly 'hardware'). It goes even further by listing the projects' maturity (concept, prototype, production DIY, production kit, production full product), and the 8 Open-o-Meter criteria along with the Open-o-Meter rating (score out of 8), which assess the level of openness of the project (Bonvoisin and Mies 2018).

Other than online databases, we also turn to the literature. One of the earliest researchers of OSHD is Kerstin Balka. In her seminal PhD thesis, she studied 104 OSHD projects to analyse project characteristics and investigate similarities and differences to OSS. She identifies the following important characteristics of OSHD projects: type and number of contributing actors; type of product in terms of the level of software code present; product complexity; licence type; degree of openness; project 'age'; level of project activity; development stage; intended audience; innovativeness; type of product in terms of industry; country/countries of development; means of communication.

Bonvoisin, Mies, Thomas, et al. (2017) also identify a variety of potential characteristics of the organisational structure of projects which could be included in a typology such as: division of labour**;** diversity of motivations to participate in a project; turnover i.e., the movement of people into and out of a project (Turnover Definition & Meaning - Merriam-Webster n.d.); qualification i.e., how 'amateur' or 'specialised' project contributors are**.** They also identify design process-related characteristics such as: willingness to involve a community; process continuity – how well the design process can continue if people leave the project; type of design process used. Lastly, they refer to the type of software used for product development.

These characteristics could potentially form interesting variables to consider for classifying OSHD projects in this study. However, these characteristics were not identified by their originators for the express purpose of classifying OSHD projects into types. Therefore, for this study, we chose to turn to OSHD experts to give a view of what characteristics they think differentiate OSHD projects. These would be aggregated with the ones presented in Table 12 before making the final selection of characteristics to be used as variables in the classification. This will then enable the development of a discrete list of the most relevant project characteristics for creating the typology.

3.4.2 Expert interviews

We carefully selected 3 individuals, each with five or more years of experience studying OSHD projects. All three of them have experience studying OSHD projects from a research perspective, while one of them also had experience participating in such projects. Their wealth of experience comes from a variety of geographical (Argentina, Italy, Germany) and research (engineering and product development, social science) foundations.

Virtual video interviews were undertaken individually with these three participants In July 2021, which lasted around 30-40 minutes each. The interviews were semi-structured, with four main scripted questions (some with sub-questions). The interviewer also used probing questions to further explore the statements of the interviewees, to increase the interviewer's understanding and to promote the free flow and elaboration of the interviewee's thinking process. We did not divulge detailed information about the study at the outset, so as not to bias the interviewees. The author gave them the following general description:

> *"My research involves studying success and best practice in OSHD projects. In this interview, I will be asking you some questions about these projects. There are lots of OSHD projects out there. I am interested in understanding the breadth of variety in these projects."*

At the end of the interview, the purpose behind it was revealed.

The four scripted questions along with a description and explanation of the rationale behind asking them are provided in Table 9.

Table 9: List of questions asked during expert interviews along with a description and an explanation of the rationale for asking those questions.

Questions asked to experts	Description and explanation of the rationale behind questions
1. Could you briefly describe your expertise with OSH? E.g., how many years you are involved and in what capacity?	To gauge the expertise of the interviewer, and their depth of understanding of the OSHD phenomenon.
2. Could you give an example of what you consider to be a very common type of OSHD project? **a. How would you explain such a project to a layperson?** **b. What are some of its defining characteristics?**	Question 2 along with sub-questions (a) and (b) where asked by the researcher at the same time. We asked the experts to identify a type of OSHD project to get an idea of whether the expert already believes certain types exist. It also provides an interesting introductory question which enables us to dig deeper with questions 2(a) and 2(b) to identify the characteristics, which is the purpose of conducting these interviews. Additionally, it would be interesting to see whether the types identified by the experts are verified by the typology created in this study.

3. Could you give two more examples of projects which you consider to be OSH, which are different to the previous one you gave, and different from each other? **a. How would you explain them to a layperson?** **b. What are their defining characteristics?** **c. Could you explain all the ways that these projects differ from each other?**	Question 3 along with sub-questions 3(a), 3(b) and 3(c) were asked by the researcher at the same time. Here, we continue asking the experts about possible other types of OSHD projects. This enables us to identify possibly more characteristics that were previously not mentioned.
4. Are there any more types of OSHD projects you can think of that we haven't talked about?	We would like the experts to exhaust all the possible types of OSHD projects they believe exist. This allows us to extract all the possible characteristics they believe differentiate project types. If they identified more types here, we followed up with questions 3(a), 3(b), and 3(c).

The profiles of the experts are shown in Table 10.

Table 10: Profiles of the three experts who were interviewed.

ID	Years of experience with OSH[46]	Description of experience with OSH
Expert 1	~16 years	Open design researcher. Interested in community building, collaborative processes and organisation. Considers themselves also a 'maker'.
Expert 2	~5 years	Started as a 'free and open source software' (FOSS) activist. An OSHD researcher, interested in social aspects of OSH, such as how people collaborate in OSHD projects. Some action research in OSHD projects.
Expert 3	~6 years	Researcher of OSHD and open design. Interested in OSHD project practices. Does not actively participate in OSHD projects.

The interviews were iteratively analysed using thematic analysis without a pre-existing framework, using the software NVivo Pro 12. A similar process as the one outlined in section 2 was carried out, using a series of coding iterations as follows:

1. Creation of very specific codes based on verbatim quotes from the interviewees
2. Development of higher-level umbrella term codes under which verbatim codes were grouped into
3. Repetition of step 3 up until a set of mutually exclusive codes depicting the characteristics of projects was generated

[46] At the time of writing: 5th August 2022.

Table 11 shows a summary of the project characteristics which were extracted from the expert interviews.

Table 11: OSHD project characteristics, according to expert interviews.

Project characteristic	Description	Number of interviewees	Number of quotes coded
Active or not	Whether project activity is taking place or not.	1	1
Goal(s)	The purpose/aim(s) of a project – what is it for?	3	73
Domain	What type of product is being developed? (electronic, mechanical, etc.)	3	12
Level and type of resources available	The kind of resources available to a project in terms of people and funding and technologies used.	3	31
Level of openness	To what extent is a project open source?	1	3
Stage	The stage a project is in, in terms of product development.	2	6
Target audience	The audience for which a project is intended. E.g., is it for a specific geographical territory, is it intended for scientists… etc.	3	7
Success	Whether a project is successful or not in terms of its impact or reaching its goals.	2	12

3.5 Step 3: Data collection for the sampled projects

This section presents how data was collected for the selected sample of projects. First, section 3.5.1 describes which variables were selected to be considered for data collection. Section 3.5.2 outlines the steps data for data collected for those variables and the rationale for the conversion of nominal variables into dummy binary variables.

3.5.1 Variables

In section 3.4.1, we presented possible characteristics which could be used as variables for classifying OSHD projects. To summarise, we aggregate these characteristics together with those identified in the expert interviews into Table 12.

Table 12: OSHD project characteristics derived from the literature and the expert interviews conducted in this study along with their source.

OSH project characteristic	Source
Country/countries of development	OSHWA; Balka, (2011)
Product category	OSHWA (project type); OHO (product category); Balka, (2011) (type of product); expert interviews.
Licence type(s)	OSHWA; Balka, (2011)
Project maturity/development stage	OHO; Balka, (2011); expert interviews
Openness	OHO; Bonvoisin and Mies (2018); Balka, (2011); expert interviews
Community involvement/ contributing actors	Bonvoisin et al. (2017); Balka, (2011)
Number of contributing actors	Bonvoisin et al. (2017); Balka, (2011)
Community structure/division of labour	Bonvoisin, Mies, Thomas, et al. (2017)
Motivations to participate	Bonvoisin, Mies, Thomas, et al. (2017)
Turnover	Bonvoisin, Mies, Thomas, et al. (2017)
Qualification	Bonvoisin, Mies, Thomas, et al. (2017)
Willingness to involve a community	Bonvoisin, Mies, Thomas, et al. (2017)
Process continuity	Bonvoisin, Mies, Thomas, et al. (2017)
Type of design process used	Bonvoisin, Mies, Thomas, et al. (2017)
Type of software used	Bonvoisin, Mies, Thomas, et al. (2017)
Means of communication	Balka, (2011)
Project 'age'	Balka, (2011)
Level of project activity	Balka, (2011); expert interviews
Intended audience	Balka, (2011); expert interviews (target audience)
Innovativeness	Balka, (2011)
Goal	Expert interviews
Resources available	Expert interviews
Success	Expert interviews

It is important to identify which of these characteristics are relevant for this study, as well as how they can be assessed from the online presence of OSHD projects. They must be translated into variables which are not only relevant to this study, but that can also be feasibly measured within the time constraints of a doctoral thesis. The balance between resource considerations and academic rigour was always an important factor in variable selection, and as such the best trade-offs in favour of academic rigour were chosen. Furthermore, the possible values each variable can have must also be considered. There is some initial guidance in the literature and the interviews, but for some project characteristics further information is needed. For example, for the project characteristic 'goal', the possible values were generated through the researcher's knowledge of OSHD projects through their research experience and were further refined through the process of data collection.

Table 13 shows how the project characteristics identified by the literature and the expert interviews were converted into variables for this study.

Table 13: Project characteristics that influence the typology, according to the literature and expert interviews conducted in this study. Alongside, the variables through which they are captured in the dataset, along with their possible values.

OSH project characteristic	**How it is captured in this study**	**Corresponding variable names and their possible values (in square brackets)**
Country/ countries of development	The country of certification and licence types for the documentation are captured in the OSHWA database, but the author does not use these as variables for the typology. The purpose of the typology is to classify projects to tailor best practice advice to them. The author does not anticipate that the country or licence type will influence this, but rather the projects' practices and product development-related characteristics.	N/A
Licence type(s)		
Community structure/ division of labour	Cannot capture these by analysing project pages online. These characteristics are excluded.	N/A
Motivations to participate		
Turnover		
Qualification		

OSH project characteristic	How it is captured in this study	Corresponding variable names and their possible values (in square brackets)
Willingness to involve a community		
Process continuity		
Type of design process used		
Type of software used		
Means of communication		
Innovativeness		
Project 'age'		
Success	As described in the previous study, success in OSHD projects is an ill-defined concept. As such we cannot assess it. Anyhow, the purpose of this study is to assess projects based on their characteristics to give them best practice advice for success, therefore it does not make sense to assess their success.	N/A
Community involvement/ contributing actors	Captured through characteristic 'Resources available'.	
Number of contributing actors		
Intended audience	Captured through characteristic 'Goal'	
Project activity	The latest date that the project was active online.	Latest activity
Goal	Perhaps not surprisingly, project goals were identified as a differentiating characteristic of OSHD projects by all interviewees. Project goals are captured by starting with a list of possible project goals identified by the interviewees such as 'for business', 'for community building' and 'for ideological reason'. The list of project goals identified by those experts was used as a starting point for identifying each of the project's main goals.	Goal 1 Goal 2 Goal 3 [For business, For work, For ideological reason, Making an educational product,

OSH project characteristic	How it is captured in this study	Corresponding variable names and their possible values (in square brackets)
	However, it was found during data collection some new project goals were identified or that project goals identified by the interviewees were not found in the projects listed, so the list of possible goals continually evolved throughout data collection. It was found that a project can have up to three goals. Those goals are sometimes explicated by the project, for example, the creator of the project 'BOWTIE PCB BADGE" states two goals in their blog: • "Implement the circuit myself" • "Design a PCB" Which were then translated by the researcher into the project goal 'Hobbyist'. Other projects had no clear goals, so they were categorised under 'unclear' (and were then later deleted), while others did not explicitly state their goals but they were able to be extracted by the researcher, e.g., for the projects created by ANAVI technology, the 'story' of the company as told by the creator on their website states of a passion for open source as well as for tinkering in their spare time. As a result, the researcher also placed the goal 'Hobbyist' for this project. From the goals identified by the experts, some were confirmed and others were dropped. Additionally, some new goals were identified by the author while collecting data on projects through their online presence, such as the goal 'for education'.	Meeting a need, Community-building, Making a low-end product, Humanitarian, Hobbyist].
Product category	Captured, although difficult to develop a nomenclature. The author named this variable 'domain'. Since a taxonomy of product levels and design domains is difficult to construct (Shenhar and Dvir 1996) and the author could not identify a simple yet comprehensive categorisation scheme of product domains, she chose to define the possible product domains as electronic, mechanical, mechatronic or crafts product.	Domain [Electronic product, Mechanical product, Mechatronic product, Crafts product]

OSH project characteristic	How it is captured in this study	Corresponding variable names and their possible values (in square brackets)
Project maturity/development stage	Can be captured by assessing what output is available by the project (e.g., design only, selling products etc.) Note that it is an OSHWA requirement that at least a prototype of the hardware must be available in order to be certified as OSH on their database. Therefore, the project stages that can be identified exclude potential pre-prototype project stages such as project inception, problem definition, concept generation, concept evaluation etc.	Output available [Design only, Selling products].
Openness	For the present study, a simple and broad assessment of openness is required for the projects. This is because a large number of projects are processed – and a quick-to-implement framework is favoured, to aid data collection. Thus, we turn to the only attempt in the literature to simply evaluate the openness of a project, the Open-o-Meter. (Bonvoisin and Mies 2018). The Open-o-Meter considers two forms of openness: product (5 criteria) and process (3 criteria), resulting in a total score out of 8. Product openness is already covered within the OSHWA definition. Therefore, we assume that by a project being listed on the OSHWA database, it already fulfils those criteria. As such, we need to assess the process openness of the projects through the 3 process openness criteria: 1. presence of version control system 2. presence of contribution guide 3. presence of issue tracking system Often, a version control system also contains an issue tracking system within it, so it is expected that variables 1 and 3 will be positively correlated.	Has version control system [Yes, No] Has contribution guide [Yes, No] Has issue tracking system [Yes, No]
Resources available	Captured through 2 lenses: people & money 1. Team composition (solo or group and whether there is a company) 2. Type of funding (if any)	Team composition [Group, Solo, Company-

OSH project characteristic	How it is captured in this study	Corresponding variable names and their possible values (in square brackets)
		group, company-solo] Funding [Yes, No]

In addition to the variables stemming from the expert interviews, the following information for each project was also collected:

- Date of data collection
- URLs to sources of information
- Researcher's comments.

The first two are useful for record-keeping and the latter was useful for synthesising information and capturing any open questions. The latter was particularly useful for establishing what possible values a variable could take. For example, the goal 'making an educational product' was identified through the research notes.

3.5.2 Data acquisition

Manual qualitative data collection was employed for collecting data about OSHD projects. The following steps were taken:

Step 1: Choose an appropriate sample size (N) of OSHD projects

Ideally, the entire population of OSHD projects (i.e., all OSHD projects that exist) should be analysed in order to be confident that the dataset captures all the variation that exists. However, due to time constraints, a smaller *N* needs to be decided. Ideally, the sample size *N* should be representative of the population, i.e., that the *N* projects sufficiently represent the entire population of OSHD projects. Two issues are identified here: (a) it is unknown whether the sample size *N* will be representative of all the projects in the list of projects scraped from the OSHWA database, and (b) that list of projects is likely not to be representative of the entire population of OSHD projects. These are further discussed in section 3.9.20.

Initially, the ambition was to analyse all the projects on the OSHWA database. However, the reality of the slow speed of manual qualitative data collection prevented this from being a possibility. To add to that, the data acquisition is only done by one researcher within the scope of a doctoral research project, posing further constraints on *N*. It was thus decided that *N* =100 would be a sufficiently large sample size. It was noted that saturation was reached by *N* =100. By using *N* =100, the end of the alphabet was missed (since the dataset was sorted by creator in alphabetical order), which could mean the sample analysed may not be representative of the OSHWA database. On average, it took the researcher about 30 minutes to collect data for each project, meaning that data collection for a sample of 100 projects took about 50 hours. This does not factor in the time taken to go back and re-collect data after variable values were changed over time. This is estimated to have taken an additional 10-20 hours.

Note that there are multiple projects by the same creator in the list of OSHWA-certified projects. For this research, only 1 project is analysed from each creator. This is to avoid skewing the results since some project characteristics may be similar between projects run by the same people. 271 unique creators were identified in the scraped list, meaning that *N* =100 accounts for 37%. As such, it cannot confidently be claimed that the sample size is representative. This is a major limitation of the study which is further discussed in section 0.

Step 2: Select *N* projects from the list scraped from the OSHWA database

Projects were ordered alphabetically by creator name. Then, projects were selected in order while excluding multiple projects from the same creator. When some projects were certified by the same creator, only one was chosen at random using a random number generator.

Step 3: Using the websites listed on the OSHWA project pages of each project analysed, along with targeted online search engine[47] queries, collect data for each variable outlined in section 3.5.1.

A Microsoft Excel spreadsheet was used to log the dataset. The starting point for data acquisition was each project's website URL listed on their OSHWA certification page. The researcher analysed this page to extract as much information in terms of the selected variables. This page was usually a GitHub page or a project or company website. The researcher also followed any additional links present on the project page opportunistically to gather more information. Additionally, online search queries (see footnote 47) were conducted to gather additional information from other web pages. For example, the researcher looked for company information databases to check whether there was a registered company in which the project was a part of, and in those cases to check how many employees that company had and whether it had funding.

Initially, each variable took on a variety of values. Every 5 or so projects, the researcher went back to look at the values of each categorical variable and attempt to synthesise them into themes. Over time, specific themes emerged for each variable, and the variables were refined. For example, 9 different project goals were identified. It is possible to use categorical variables in classification. However, an issue occurs regarding the prospect of using the variables as they are in the dataset of the present study. This issue involves the fact that each project analysed was found to have up to

[47] www.google.com was used as a search engine.

three project goals. Further, sometimes a goal represented by Goal 1 for a case was for other cases represented under Goal 2. To illustrate, sometimes Goal 1 took the value *For business* for one project but other times Goal 2 took the value *For business* for another project. As such the variables Goal 1, Goal 2 and Goal 3 cannot be compared with each other. To overcome this issue, 'dummy' variables (i.e., binary variables) were created which can take a value of 1 or 0. This indicates whether the phenomenon indicated by the variable is present in the project or not (1 or 0 respectively). This was done for all the variables used for data collection, to simplify the analysis. Table 14 shows how the variables collected for each case were translated into dummy variables.

Table 14: Dummy variables stemming from the original variables.

Original variable names and their possible values (in square brackets)	**Dummy variables**	**Rationale**
Latest activity	N/A	Not used in analysis
Goal 1 Goal 2 Goal 3 [For business, For work, For ideological reason, Making an educational product, Meeting a need, Community-building, Making a low-end product, Humanitarian, Hobbyist].	1. Goal: For business 2. Goal: For work 3. Goal: For ideological reason 4. Goal: Making an educational product 5. Goal: Meeting a need 6. Goal: Community-building 7. Goal: Making a low-end product 8. Goal: Humanitarian 9. Goal: Hobbyist	Each possible goal became an individual dummy variable. Each project had 1-3 goals.
Domain [Electronic product, Mechanical product, Mechatronic product, Crafts product]	10. Mechanical product 11. Crafts product 12. Electronic product 13. Mechatronic product	Each possible domain became a dummy variable.
Team composition [Group, Solo, Company-group, company-solo] Funding [Yes, No]	14. Group 15. Company 16. Funding	Team composition was split into two – company and group.
Output available [Design only, Selling products].	17. Selling	Was already binary.
Has version control system [Yes, No] Has contribution guide [Yes, No] Has issue tracking system [Yes, No]	18. Has version control system 19. Has contribution guide 20. Has issue tracking system	Were already binary.

Table 15 offers a description of each variable, including information about how each one was selected to be set to 0 or 1 when analysing a project.

Table 15: Description of dummy variables.

Variable name	**Description (All are binary i.e. Yes/No)**
Goal: For business	Goal: For business = 1 if the project team is selling that OSH or they are selling that OSHD as part of a bigger product (e.g. the OSHD is a component of an overall product), or if that OSHD is contributing to their other business.
Goal: For work	Goal: For work = 1 if that OSH was created to serve the creator's work. E.g., it could be instrumentation which was developed to be used for conducting lab experiments.
Goal: For ideological reason	Goal: For ideological reason = 1 if that OSH was created for an ideological reason, activism, etc. For example, if they specifically created an OSH product because they are ethically opposed to closed source and wanted to create an open source alternative.
Goal: For meeting a need	Goal: For meeting a need = 1 if it was expressly mentioned that OSH was created to fulfil a need the originator(s) have identified. Many times, this is a personal need.
Goal: Community-building	Goal: Community-building = 1 if that OSHD project was started with the purpose of building a community around the project.
Goal: Making a low-end product	Goal: Making a low-end product = 1 if the purpose for developing that OSH is to develop a cheap or low-cost product, in some occasions a cheaper version of an alternative product that exists on the market.
Goal: Humanitarian	Goal: Humanitarian = 1 if the OSH was developed for helping improve human welfare.
Goal: Hobbyist	Goal: Hobbyist = 1 when the OSHD project was created because developing OSH products is a personal hobby the originator(s) do for fun. This is usually identified by analysing the profile of the originator(s). Originator(s) of such projects usually have a 'day job' and develop OSH of low complexity that can be easily made at home.
Mechanical product	Mechanical product =1 for projects which develop products which adhere to the definition of 'mechanical' by Collins Dictionary: *A mechanical device has parts that move when it is working, often using power from an engine or from electricity.* https://www.collinsdictionary.com/dictionary/english/mechanical This variable is also = 1 for projects whose products do not have moving parts but have been designed through an engineering design process. This could include products such as fittings and shoe soles composed of multiple parts. It is worth noting that this variable = 0 for projects whose products have electronic components (for

Variable name	Description (All are binary i.e. Yes/No)
	mechanical products which also include electrical components, see 'Domain_Mechatronics').
Crafts product	Crafts product =1 for products which are made exclusively from every-day craft materials such as yarn, paper, cardboard and clay. They do not include electronic or mechanical components and do not require engineering design skills.
Electronic product	Electronic product =1, for projects whose products align with the definition of 'electronic device' by Collins Dictionary: *"An electronic device has transistors or silicon chips which control and change the electric current passing through the device."* https://www.collinsdictionary.com/dictionary/english/electronic-device This variable includes electronic devices such as printed circuit boards (PCBs). It also includes electronic devices with non-moving casings or housings (for example, a PCB with a cover) and electronic devices accompanied by a paper component (e.g., a notebook with electronics inside it). Electronic devices with simple buttons or joysticks (basic switches) are also considered in this category.
Mechatronic product	Mechatronic product =1 includes projects whose products are devices which have both electronic component(s) and mechanical component(s) (see Electronic product and Mechanical product). This category includes mechatronic devices such as 3D printers, which contain both moving parts and electronics for controlling movement. It would also contain products such as a laptop or tablet with casings which requires substantial mechanical design.
Group	If project team (i.e., contributors) > 1 then Group = 1. Else = 0. Can identify how many people were part of project team by looking at contributors on the project hosting repository, or through the text in the README files listing who contributed/owns the copyright in the project.
Company	Company =1 if a company was present within which the project takes place.
Funding	Funding =1 if the project has crowdfunding, sponsors e.g., Patreon or GitHub, grant(s), investment (angel investors or publicly traded company. Funding = 1 also if the project company has funding but it is for another project or it is unknown if it is for this project or not. If no funding was identified = 0.
Selling	Selling =1 if the OSH is being sold either as a DIY kit or a fully assembled product.

List-wise deletion of projects was employed in cases of missing data points. Namely, around 3 projects were eliminated from the data collection spreadsheet because the insights>contributors tab on GitHub was not loading as well as around 3 projects for which project goals could not be identified. The data acquisition process continued until data was collected for 100 projects. The number of projects having each dummy variable =1 is shown in Figure 10.

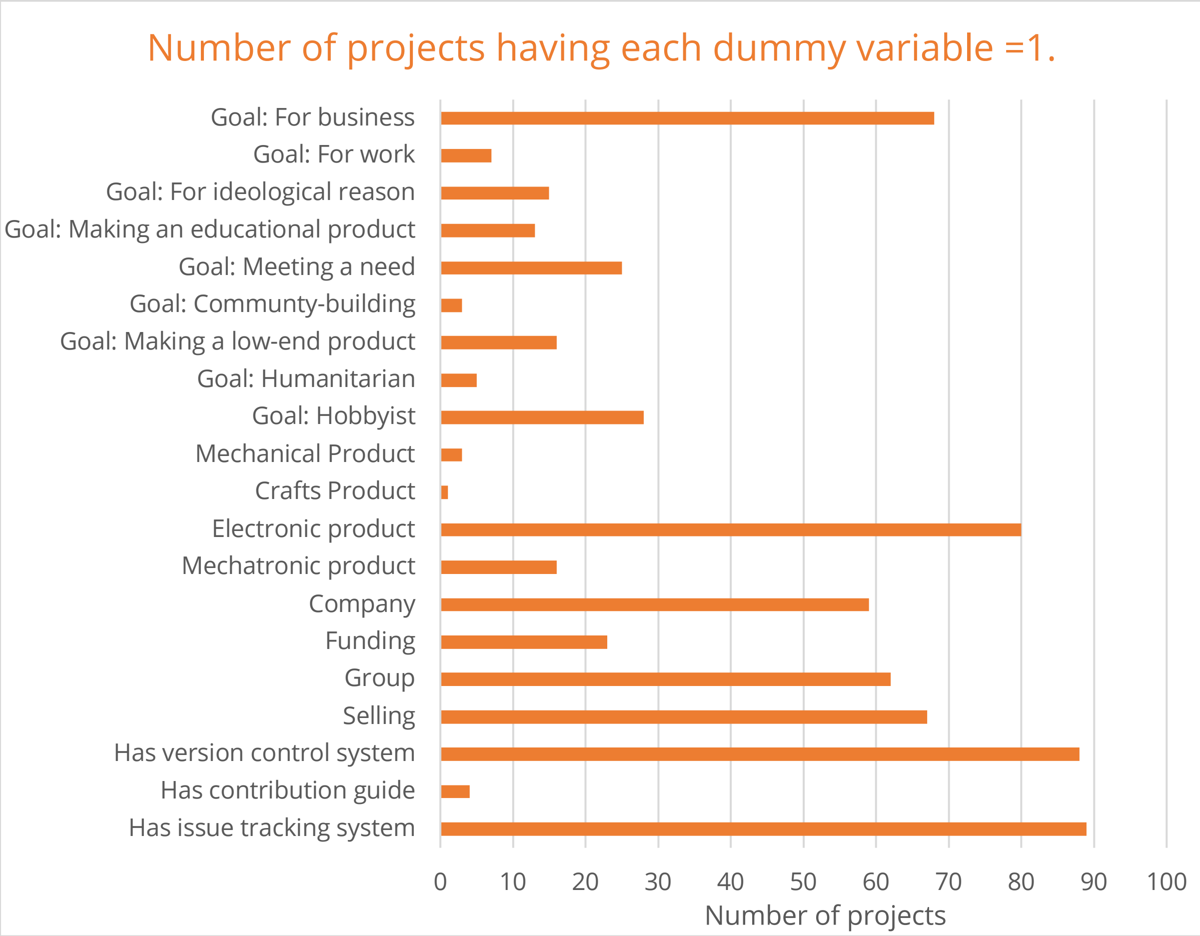

Figure 10: Bar graph showing how many projects contained each variable out of the 100 projects that were analysed.

3.6 Step 4: Classification of OSHD projects based on their characteristics

There are several ways to perform a typology including univariate, bivariate and multivariate methods, with the latter being the preferred way (Mandara 2003). Multivariate methods involve classifying cases by evaluating each on a set of variables (Mandara 2003). This set of methods requires no previous knowledge of each type's typical pattern of behaviour. In this study, the author chose to use cluster analysis because it is one of the most popular and preferred families of multivariate methods used for classification (Mandara 2003).

To perform cluster analysis, the author chose to use SPSS as a quantitative data analysis software since it is powerful, able to deal with large datasets, relatively easy to use (Sarstedt and Mooi 2019), and is available to use via a licence from the University of Bath.

The structure of this section is as follows: section 3.6.1 introduces cluster analysis as a family of methods which can be used for conducting classification; section 3.6.2 outlines the process of selecting which variables to use for clustering; section 3.6.3 describes the selection of linkage algorithm and distance metric for the chosen cluster method; and section 3.6.4 shows the outputs given by performing the cluster analysis on SPSS – a dendrogram and an agglomeration schedule.

3.6.1 Cluster analysis

Cluster analysis is not a singular technique which is simply deployed and the result comes out the other side – it is a complex family of methods which heavily relies on critical decisions to be taken by the researcher to have meaningful results (Van Ryzin 1995). There are also many ways of classifying cluster analysis methods according to different criteria. One practical way of differentiating between different cluster analysis methods is by splitting them into hierarchical and partitioning methods. An important distinction between the two is that in the former if a case is allocated to a certain cluster, it is impossible to reassign that to another cluster (Sarstedt and Mooi 2019).

One of the most common partitioning methods is called *k-means clustering.* This method requires a priori knowledge of the number of clusters (*k)* required to be extracted from the data, which is used as an input (Sarstedt and Mooi 2019). This method starts by randomly assigning the cases into the *k* clusters. It then iterates by reassigning the cases to the other clusters, aiming to minimise the "within-cluster variation" (Sarstedt and Mooi 2019). It repeats this process until it finds the best solution with the smallest within-cluster variation in each cluster. This method is not suitable for this study because *k* is not known a priori. This method also uses Euclidean distances to calculate the separation between cases, which is unsuitable for binary data (Sarstedt and Mooi 2019).

Hierarchical clustering methods are typically characterised by a dendrogram: a tree-like diagram created through the analysis (Sarstedt and Mooi 2019). See Figure 11 for an illustration of a simple dendrogram. Most hierarchical clustering methods are agglomerative (bottom-up), meaning that clusters are sequentially formed by merging different cases over several steps until all cases are merged into one cluster (Sarstedt and Mooi 2019). Cases are merged based on their similarity, in other words, the distance between the cases. The distance between a newly formed cluster to a case or indeed another cluster is defined through a linkage algorithm (Sarstedt and Mooi 2019). This is illustrated by looking at Figure 11 from left to right. Other clustering methods are divisive (top-down), starting from one large cluster of all the cases which over a series of steps splits into smaller clusters until each cluster comprises one case (Sarstedt and Mooi 2019). This is illustrated by looking at Figure 11 from right to left. Divisive hierarchical clustering methods are not implemented in commonly used statistical software such as SPSS and are rarely used because they are computationally intensive. (Sarstedt and Mooi 2019). Therefore, agglomerative clustering is deemed more suitable for this study.

The dendrogram can also support the decision of how many clusters should be selected for the best cluster solution. Drawing a vertical line on the dendrogram at different points on the x-axis results in a different number of clusters for the solution. The number of clusters is represented by the number of horizontal lines that are being 'cut' by the vertical line drawn. A good solution is indicated by a large distance along the x-axis (i.e., length) of the lines being cut. In the example in Figure 11, a good solution might be the two or three-cluster solution. Ideally, it is desirable to observe short lines in the first few mergers of cases, followed by longer lines near the right-hand side. Longer lines essentially represent dissimilarity across cases/clusters making it more 'difficult' to merge them in the same cluster. This indicates that the clusters are distinct from each other.

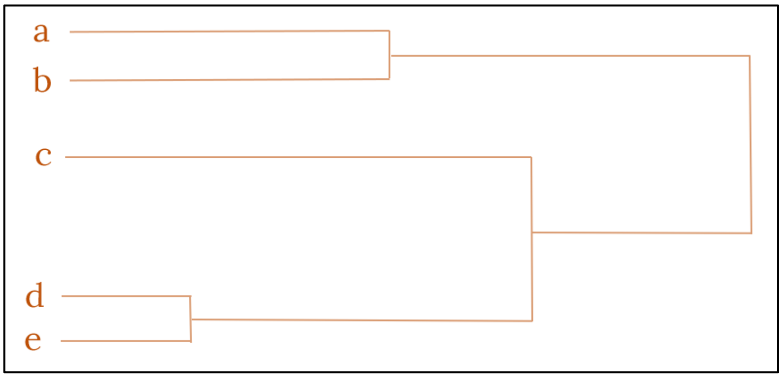

Figure 11: A simple dendrogram for the hierarchical clustering of cases a, b, c, d, and e (for illustration purposes, not based on a real hierarchical clustering application).

3.6.2 Selection of clustering variables

Several considerations need to be made to select only the most suitable variables to be used for clustering. Sections 3.6.2.1 and 3.6.2.2 describe the rationale for the exclusion of certain variables. Section 3.6.2.3 briefly addresses the consideration of standardisation and section 3.6.2.4 provides the final list of clustering variables.

3.6.2.1 Exclusion of highly correlated variables

Variables which are highly correlated to each other should not both be used, as this would skew the dataset (Sarstedt and Mooi 2019). This is because the relationship which connects those variables would be overrepresented in the dataset. In the case of correlated variables, only one of the two should be used. Phi coefficients can be used to establish correlation for binary variables (Verma and Abdel-Salam, 2019). The correlations between the variables are tabulated in Table 16 which shows that the variables *Goal: For business* and *Selling product* are highly correlated with a statistically significant (<0.001) Phi coefficient of .841. The variable *Goal: For business* was kept for the clustering. The variables *Electronic Product* and *Mechatronic product* were also highly correlated with a statistically significant (<0.001) Phi coefficient value of -.873. In this case, the variable *Electronic Product* was kept for the clustering[48]. The variables *Has version control system* and *Has issue tracking system* were also highly correlated with a statistically significant Phi coefficient value of .854, but these were excluded regardless due to being swamping variables (see next section 3.6.2.2).

[48] According to Sarstedt & Mooi (2019), the minimum threshold for highly correlated variables is a correlation coefficient value of 0.9. The researcher has used their judgement here to make exceptions for the values of .841 and .873 since they are extremely close to this threshold.

Table 16: Phi coefficients between variables and their statistical significance. Values in lighter (green) colour are statistically significant at the 0.05 level; values in darker (green) colour are statistically significant at the 0.01 level. The values showing a Phi coefficient above the threshold[48] which is also statistically significant is further indicated in bold font.

		Goal: For business	Goal: For Work	Goal: For Ideological Reason	Goal: Making an Educational Product	Goal: Meeting a Need	Goal: Community building	Goal: Making a Low End Product	Goal: For Humanitarian Reason	Goal: Hobbyist	Mechanical Product	Crafts Product	Electronic Product	Mechatronic Product	Company	Funding	Group of people	Selling Product	Has Version Control System	Has Contribution Guide	Has Issue Tracking System
Goal: For business	Phi coefficient																				
Goal: For Work	Phi coefficient	-.232	--																		
	Significance	.020																			
Goal: For Ideological Reason	Phi coefficient	.108	-.115	--																	
	Significance	.280	.259																		
Goal: Making an Educational Product	Phi coefficient	.074	-.106	-.079	--																
	Significance	.460	.289	.429																	
Goal: Meeting a Need	Phi coefficient	.000	-.158	.016	-.155	--															
	Significance	1.000	.113	.872	.122																
Goal: Community-building	Phi coefficient	-.131	-.048	.090	-.068	-.102	--														
	Significance	.191	.629	.367	.497	.310															
Goal: Making a Low End Product	Phi coefficient	-.110	.094	-.183	.075	-.063	.083	--													
	Significance	.272	.347	.067	.456	.529	.406														
Goal: For Humanitarian Reason	Phi coefficient	-.138	.117	.032	-.089	-.132	-.040	.150	--												
	Significance	.168	.242	.748	.375	.185	.687	.133													

		Goal: For business	Goal: For Work	Goal: For Ideological Reason	Goal: Making an Educational Product	Goal: Meeting a Need	Goal: Community building	Goal: Making a Low End Product	Goal: For Humanitarian Reason	Goal: Hobbyist	Mechanical Product	Crafts Product	Electronic Product	Mechatronic Product	Company	Funding	Group of people	Selling Product	Has Version Control System	Has Contribution Guide	Has Issue Tracking System
Goal: Hobbyist	Phi coefficient	-.432	.003	-.200	-.109	-.206	.021	.032	-.143	--											
	Significance	<.001	.972	.046	.277	.040	.835	.752	.153												
Mechanical Product	Phi coefficient	-.131	.182	-.074	-.068	-.102	.313	.083	.229	.021	--										
	Significance	.191	.070	.460	.497	.310	.002	.406	.022	.835											
Crafts Product	Phi coefficient	-.147	-.028	-.042	-.039	.174	-.018	-.044	-.023	-.063	-.018	--									
	Significance	.143	.783	.673	.698	.082	.860	.661	.818	.531	.860										
Electronic Product	Phi coefficient	.032	.039	-.140	.045	-.058	-.059	-.055	-.229	.256	-.352	-.201	--								
	Significance	.748	.695	.161	.656	.564	.558	.585	.022	.010	<.001	.044									
Mechatronic Product	Phi coefficient	.065	-.120	.199	-.006	.063	-.077	.033	.150	-.272	-.077	-.044	**-.873**	--							
	Significance	.513	.231	.047	.948	.529	.443	.743	.133	.006	.443	.661	**<.001**								
Company	Phi coefficient	.431	-.170	.236	.020	-.176	.147	-.080	.005	-.431	.147	-.121	-.315	.308	--						
	Significance	<.001	.090	.018	.842	.078	.143	.425	.963	<.001	.143	.228	.002	.002							
Project has funding	Phi coefficient	.324	-.057	.303	.001	-.041	-.096	-.174	.093	-.235	.043	-.055	-.083	.086	.359	--					
	Significance	.001	.570	.002	.994	.681	.336	.082	.354	.019	.666	.583	.406	.392	<.001						
Group of people	Phi coefficient	.302	-.027	.271	.058	-.167	.138	-.052	-.009	-.475	.017	-.128	-.237	.285	.646	.281	--				
	Significance	.003	.784	.007	.565	.096	.169	.605	.925	<.001	.866	.199	.018	.004	<.001	.005					
Selling Product	Phi coefficient	**.841**	-.224	.176	.018	.012	-.001	-.042	-.132	-.415	-.126	-.143	.074	.016	.366	.282	.283	--			
	Significance	**<.001**	.025	.079	.854	.902	.990	.676	.188	<.001	.208	.152	.457	.871	<.001	.005	.005				

		Goal: For business	Goal: For Work	Goal: For Ideological Reason	Goal: Making an Educational Product	Goal: Meeting a Need	Goal: Community building	Goal: Making a Low End Product	Goal: For Humanitarian Reason	Goal: Hobbyist	Mechanical Product	Crafts Product	Electronic Product	Mechatronic Product	Company	Funding	Group of people	Selling Product	Has Version Control System	Has Contribution Guide	Has Issue Tracking System
Has Version Control System	Phi coefficient	.011	.101	.069	-.040	-.071	.065	-.007	-.339	.230	-.115	-.272	.354	-.259	-.058	-.091	-.036	.134	--		
	Significance	.916	.311	.491	.687	.477	.516	.946	<.001	.021	.248	.006	<.001	.010	.565	.365	.723	.182			
Has Contribution Guide	Phi coefficient	.140	-.056	.200	.073	.000	-.036	.050	.187	-.127	-.036	-.021	-.281	.329	.170	.131	.160	.143	-.082	--	
	Significance	.161	.575	.045	.466	1.000	.720	.616	.061	.203	.720	.837	.005	.001	.089	.190	.110	.152	.414		
Has Issue Tracking System	Phi coefficient	.033	.096	.148	-.054	-.092	.062	-.021	-.359	.219	-.126	-.286	.304	-.195	-.033	-.112	-.012	.093	**.854**	-.091	--
	Significance	.742	.335	.140	.588	.356	.536	.834	<.001	.028	.209	.004	.002	.051	.740	.264	.906	.352	**<.001**	.361	

3.6.2.2 *Exclusion of swamping variables*

Some variables are 'swamping' variables i.e., they have the same value for most of the projects. The swamping variables were identified to be: *Goal: Community-building*; *Goal: For work*; *Goal: For humanitarian reason*; *Mechanical product*; *Has version control system*; *Has contribution guide*; *Crafts product*; and *Has issue tracking system*. For these, more than 88% of projects had the same value. As such, they are not expected to influence the clustering much.

3.6.2.3 *Standardisation*

The variables do not need to be standardised since they are already all in the same scale (binary, i.e. 0 or 1).

3.6.2.4 *List of chosen clustering variables*

Excluding highly correlated and swamping variables, we are presented with a list of 9 variables to be used in the clustering. These are:

1. *Goal: For business*
2. *Goal: For Ideological Reason*
3. *Goal: Making an Educational Product*
4. *Goal: Meeting a Need*
5. *Goal: Making a Low End Product*
6. *Goal: Hobbyist*
7. *Electronic Product*
8. *Company*
9. *Funding*

3.6.3 Linkage algorithms and distance metrics

Since it was chosen to use agglomerative hierarchical clustering for this study, the next step is to select a linkage algorithm. Since they influence how cases are placed into clusters, careful consideration should be employed for an appropriate selection of linkage algorithm. Table 17 describes the most popular linkage algorithms.

Table 17: Descriptions of linkage algorithms for hierarchical clustering along with a discussion of their suitability. Adapted from Sarstedt and Mooi (2019).

Linkage algorithm	Description	Discussion of suitability
Single linkage	Known as "nearest neighbor" in SPSS. The distance between two clusters is based on the smallest distance between any two cases within the two clusters.	Tends to form one very large cluster and other smaller clusters which contain only a few objects each. This could be useful for outlier detection.

Linkage algorithm	Description	Discussion of suitability
Complete linkage	Known as "furthest neighbor" in SPSS. The distance between two clusters corresponds to the largest distance between any two cases in the two clusters.	Since this algorithm considers maximum distances, it is strongly affected by outliers.
Average linkage	Known as "between-groups linkage" in SPSS. The distance between two clusters is equal to the average distance between all pairs of cases in the two clusters.	Average linkage and centroid linkage often produce clusters with low within-cluster variance and similar sizes. While they are affected by outliers, since both of these linkage algorithms are based upon average distances, it is less so than complete linkage.
Centroid linkage	The centroid, i.e., the geometric centre of each cluster is computed by calculating the average values of the clustering variables of all the cases in a certain cluster. The distance between two clusters equals the distance between the centroids of each cluster.	
Ward's linkage	This linkage algorithm differs from the previous ones in that instead of combining the most similar cases sequentially, it instead combines those whose merger increases the within-cluster variance at the smallest possible level.	Similar to average and centroid linkage, Ward's linkage also tends to yield clusters of similar size. They also tend to have a similar within-cluster variance. Research has shown that this method performs very well, but it is sensitive to outliers and highly correlated variables.

The different linkage algorithms effectively represent the logic by which cases are merged into clusters. In all cases, that logic involves calculating a distance between cases, to implement it. There are various measures of calculating those distances, and this is done using measures of similarity or dissimilarity. These measures differ depending on the data type. For this study, binary variables were used as described in section 3.5.2.

After carefully studying a variety of papers in the literature employing hierarchical clustering with binary variables, the author observed no clear consensus as to which linkage method and distance metric should be used for clustering binary variables. Sarstedt and Mooi (2019) advise using Ward's linkage to obtain equally-sized clusters in conjunction with similarity measures called matching coefficients such as the simple matching coefficient, the Jaccard coefficient, the Russel Rao coefficient, Yule's Q coefficient or the Kulczynski coefficient. Cibulková et al. (2019) employ average linkage for a dataset of binary variables and obtained good clustering solutions using Euclidean distance and simple matching coefficient. Tamasauskas et al. (2012) investigated the performance of hierarchical clustering using a variety of linkage algorithms and distance measures and observed good performance with several combinations. Multiple researchers also warn against the usage of single linkage (Cibulková et al. 2019; Hands and Everitt 1987).

Ward's linkage was selected as a linkage algorithm for this study, since it demonstrated good performance and is often recommended in the literature, particularly for binary variables (Sarstedt and Mooi 2019; Hands and Everitt 1987; Tamasauskas et al. 2012; Henry et al. 2015). These studies employed a variety of different distance measures, but the author ultimately chose Squared Euclidean distance for three reasons: Ward's linkage is often used with Squared Euclidean distances (Sarstedt and Mooi 2019); it is the default option for hierarchical clustering of binary variables in SPSS; the author ran the cluster analysis using Ward's linkage with a variety of different distance metrics available in SPSS, and this one provided the most coherent results. According to (Sneath and Sokal 1973), the researcher's judgement of the result is of sound importance to the selection of distance measure.

3.6.4 Hierarchical clustering in SPSS

Hierarchical cluster analysis using Ward's linkage and Squared Euclidean distance for binary variables was carried out in SPSS. This yields a dendrogram – a graphical representation of the cluster solution (see section 3.6.1 for more information on dendrograms) – shown in Figure 12.

At first glance, the dendrogram indicates a good cluster solution, represented by the short distances on the x-axis at the beginning of the clustering (left-hand side) followed by a relatively large distance on the x-axis for the two and three-cluster solutions.

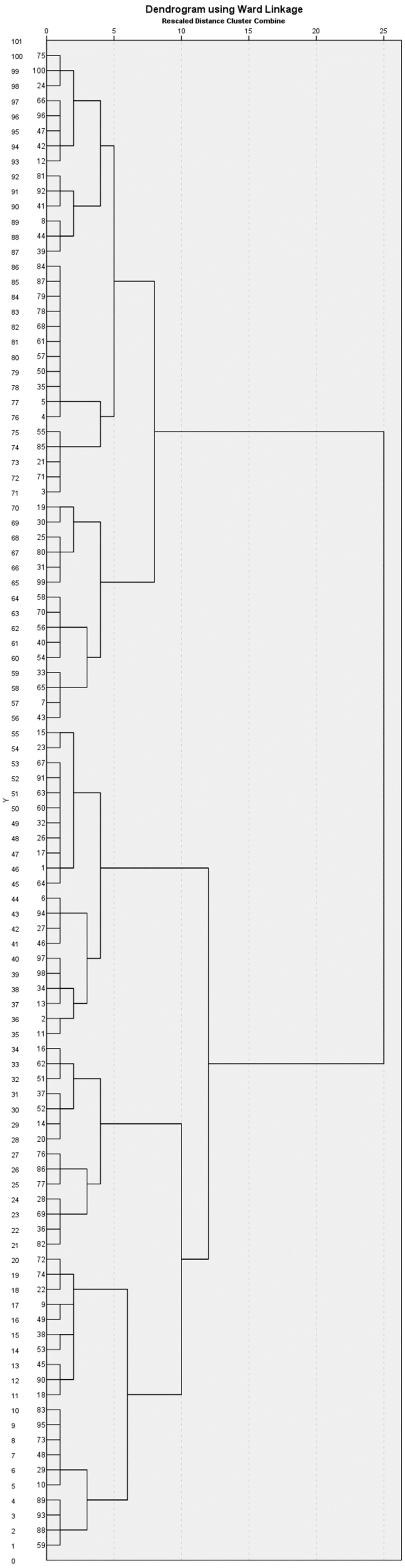

Figure 12: Dendrogram of hierarchical clustering using Ward's linkage and Squared Euclidean distance.

The cluster analysis also yields the agglomeration schedule, a numerical representation of the cluster solution, displayed in Table 18. It is best to explain what it represents by describing this specific example. In the first stage, cases 75 and 100 are combined because their merging leads to the minimum possible within-cluster variance after merging (according to Ward's method – see section 3.6.3). The cluster created from this merging next appears in stage 60. In stage 69, the clusters created in stages 32 and 30 are merged. The cluster created from this joining appears next in stage 86.

The agglomeration schedule can be useful when it comes to identifying the optimum number of clusters for the cluster solution. To find this, we look for the high step changes between coefficients. This represents how different the clusters being merged going from one stage to the next. The highest step change indicates the most suitable number of clusters for the cluster solution (IBM Corporation 2021a). Looking at the column titled 'Coefficients', it can be seen that the highest step change is at stage 98 (coefficient step change = 156.070 - 123.313= 32.757). As such, from the agglomeration schedule, we can understand that a two-cluster solution is the most suitable one. This is also confirmed by the dendrogram in Figure 12, where two clearly separated clusters can be seen near the right-hand side. However, a researcher's 'practical reasoning' must also be employed when deciding how many clusters to select for the cluster solution (Sarstedt and Mooi 2019). Having analysed the results of both the two-cluster and three-cluster solutions, the author deemed that the two-cluster solution was too generic, whereas the three-cluster solution gave a bit more insight into the variation between OSHD projects. It is for this reason that the author chose the three-cluster solution to be the optimal one. Additional information which helps support this decision includes the fact that the three-cluster solution shows the second highest step-change in the agglomeration schedule, and that the ratio between the largest and smallest cluster is not extremely high (~2).

Table 18: Agglomeration schedule for hierarchical clustering using Ward's Linkage and Squared Euclidean distance. The agglomeration schedule indicates that the optimal solution is at stage 98.

Agglomeration Schedule						
Stage	Cluster Combined		Coefficient	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	75	100	0.000	0	0	60
2	97	98	0.000	0	0	3
3	34	97	0.000	0	2	41
4	66	96	0.000	0	0	24
5	83	95	0.000	0	0	13
6	6	94	0.000	0	0	75
7	81	92	0.000	0	0	14
8	67	91	0.000	0	0	23

Agglomeration Schedule						
9	45	90	0.000	0	0	62
10	84	87	0.000	0	0	12
11	55	85	0.000	0	0	70
12	79	84	0.000	0	10	16
13	73	83	0.000	0	5	18
14	41	81	0.000	0	7	78
15	25	80	0.000	0	0	74
16	78	79	0.000	0	12	17
17	68	78	0.000	0	16	22
18	48	73	0.000	0	13	36
19	21	71	0.000	0	0	46
20	58	70	0.000	0	0	30
21	28	69	0.000	0	0	72
22	61	68	0.000	0	17	28
23	63	67	0.000	0	8	26
24	47	66	0.000	0	4	37
25	33	65	0.000	0	0	73
26	60	63	0.000	0	23	29
27	16	62	0.000	0	0	61
28	57	61	0.000	0	22	31
29	32	60	0.000	0	26	42
30	56	58	0.000	0	20	69
31	50	57	0.000	0	28	35
32	40	54	0.000	0	0	69
33	38	53	0.000	0	0	76
34	37	52	0.000	0	0	71
35	35	50	0.000	0	31	40
36	29	48	0.000	0	18	43
37	42	47	0.000	0	24	39
38	8	44	0.000	0	0	63
39	12	42	0.000	0	37	82
40	5	35	0.000	0	35	48
41	13	34	0.000	0	3	79
42	26	32	0.000	0	29	44
43	10	29	0.000	0	36	87
44	17	26	0.000	0	42	47
45	15	23	0.000	0	0	77
46	3	21	0.000	0	19	70
47	1	17	0.000	0	44	67
48	4	5	0.000	0	40	89
49	31	99	0.500	0	0	74
50	89	93	1.000	0	0	64
51	76	86	1.500	0	0	65

Agglomeration Schedule						
52	36	82	2.000	0	0	72
53	72	74	2.500	0	0	66
54	9	49	3.000	0	0	80
55	27	46	3.500	0	0	75
56	7	43	4.000	0	0	73
57	19	30	4.500	0	0	81
58	14	20	5.000	0	0	71
59	2	11	5.500	0	0	79
60	24	75	6.167	0	1	82
61	16	51	6.833	27	0	84
62	18	45	7.500	0	9	76
63	8	39	8.167	38	0	78
64	88	89	9.000	0	50	68
65	76	77	9.833	51	0	88
66	22	72	10.667	0	53	83
67	1	64	11.556	47	0	77
68	59	88	12.472	0	64	87
69	40	56	13.672	32	30	86
70	3	55	14.872	46	11	89
71	14	37	16.122	58	34	84
72	28	36	17.372	21	52	88
73	7	33	18.622	56	25	86
74	25	31	19.872	15	49	81
75	6	27	21.122	6	55	85
76	18	38	22.456	62	33	80
77	1	15	24.112	67	45	93
78	8	41	25.779	63	14	91
79	2	13	27.445	59	41	85
80	9	18	29.517	54	76	83
81	19	25	31.600	57	74	90
82	12	24	33.684	39	60	91
83	9	22	36.079	80	66	95
84	14	16	38.519	71	61	92
85	2	6	41.203	79	75	93
86	7	40	44.030	73	69	90
87	10	59	46.880	43	68	95
88	28	76	50.083	72	65	92
89	3	4	54.070	70	48	94
90	7	19	58.626	86	81	96
91	8	12	63.542	78	82	94
92	14	28	68.471	84	88	97
93	1	2	73.611	77	85	98
94	3	8	79.857	89	91	96

Agglomeration Schedule						
95	9	10	86.557	83	87	97
96	3	7	96.679	94	90	99
97	9	14	108.655	95	92	98
98	1	9	123.313	93	97	99
99	1	3	156.070	98	96	0

3.7 Typology of OSHD projects

This section presents three types of OSHD projects, identified through hierarchical cluster analysis using a set of 9 variables carefully selected through literature and interviews with experts, in conjunction with accounting for the feasibility of data collection, correlations between variables and swamping effects.

There are 35, 47 and 18 projects in Clusters 1, 2, and 3 respectively, as illustrated in Figure 13.

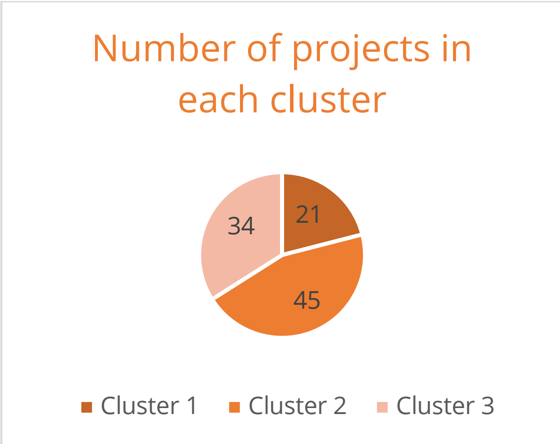

Figure 13: Pie chart illustrating the distribution of cases across clusters.

The three-cluster solution is summarised in Figure 14, which shows a bar chart illustrating the composition of each cluster in terms of the percentage of projects for which each variable had a value of 1. In this and all the other graphs of the cluster compositions that follow in this section, all the variables that were collected are shown, not just the ones used for clustering. This is to aid the understanding of the cluster's features.

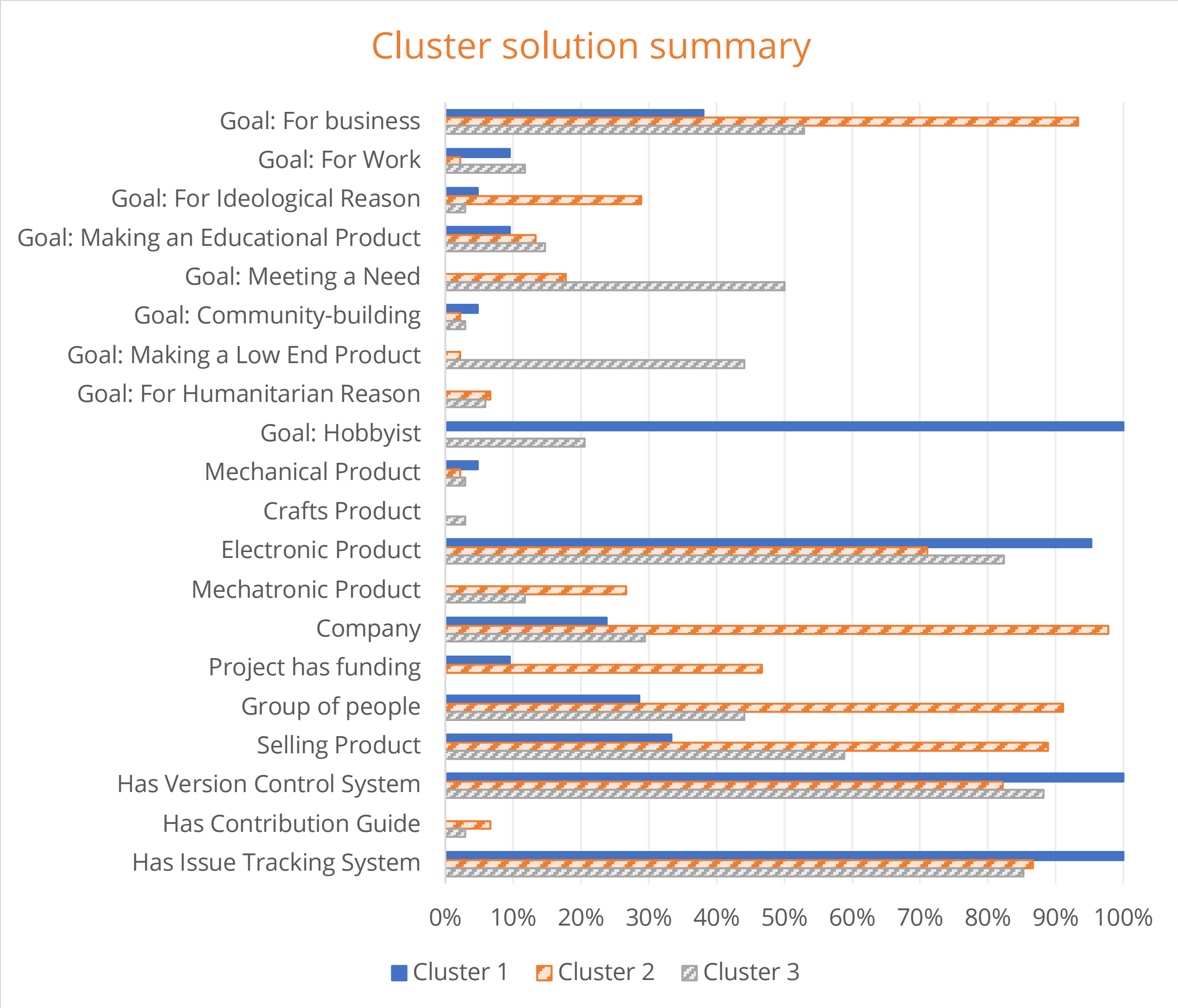

Figure 14: The percentage of projects which had a value of 1 for each of the variables in each cluster.

The following sections 3.7.1, 3.7.2 and 3.7.3, describe each of the three clusters generated by the cluster analysis in detail. The clusters are also called project types interchangeably. Descriptors for each cluster were generated by examining the variables that were present or not present within each cluster.

3.7.1 Cluster 1: Hobbyist electronics

Figure 15 shows a bar graph illustrating the composition of cluster 1 in terms of the presence of each binary variable. To understand the dominating features of this cluster, we look at what variables appear in high frequencies in the projects within it. From this graph, it can be observed that 100% of the projects in the cluster have the goal 'Hobbyist' and 95% have the domain 'Electronic product' (the remaining 5% are mechanical products). 100% of projects in this cluster have version control systems and issue tracking systems. However, the variables representing these two systems appear in relatively high frequencies across all clusters, so no particular emphasis is placed on them when it comes to identifying the unique characteristics of this cluster. As such, the defining variables for the projects in Cluster 1 are *Goal: Hobbyist* and *Electronic product*. Therefore, the author ascribed the name 'Hobbyist Electronics' to this cluster.

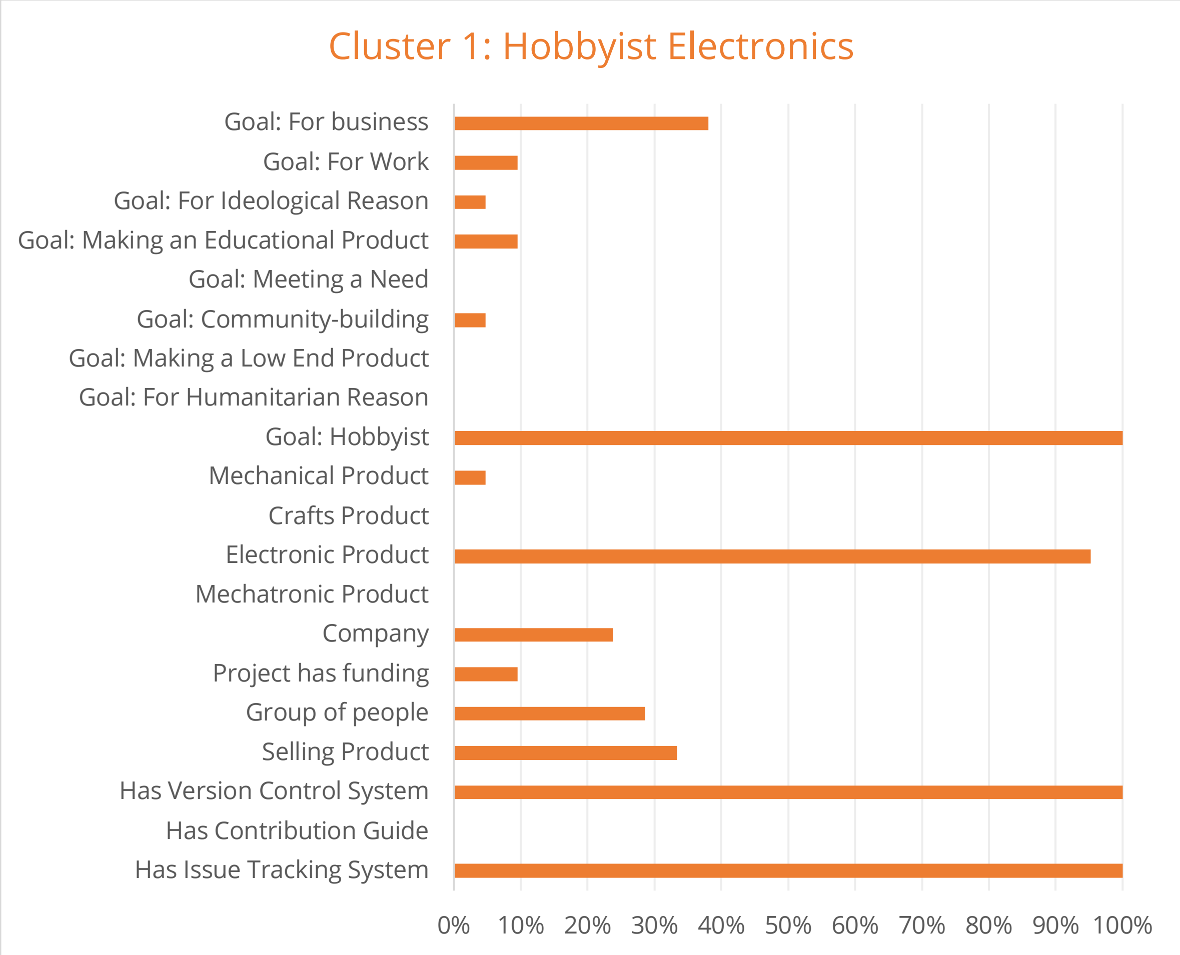

Figure 15: Composition of cluster 1.

In terms of goals, other than 'Hobbyist', 38% of the projects in cluster 1 have the goal 'For business'; 10% 'For work'; 10% 'Making an educational product'; 5% 'For ideological reason'; 5% 'Community-building'.

We also observe that 33% of projects within this cluster are selling products, 29% have a group of people participating, and 24% have a company. Only 10% of these projects have funding, while none have contribution guides.

3.7.2 Cluster 2: Professional projects

Figure 16 shows a bar graph illustrating the composition of cluster 2 in terms of the presence of each binary variable. To understand the dominating features of this cluster, we look at what variables appear in high frequencies in the projects within it. As in the previous cluster, we exclude the variables 'Has version control system' and 'Has issue tracking system' when looking at the dominating variables. From this graph, it can be observed that 98% of the projects in the cluster have a company associated with the project, 93% have the goal 'For business', while 91% are group projects. 89% of these projects are selling a product. Since it contains, as a majority, projects which have sales, have business as a goal, and involve a group of people working together within a company, Cluster 2 is given the name 'Professional projects'.

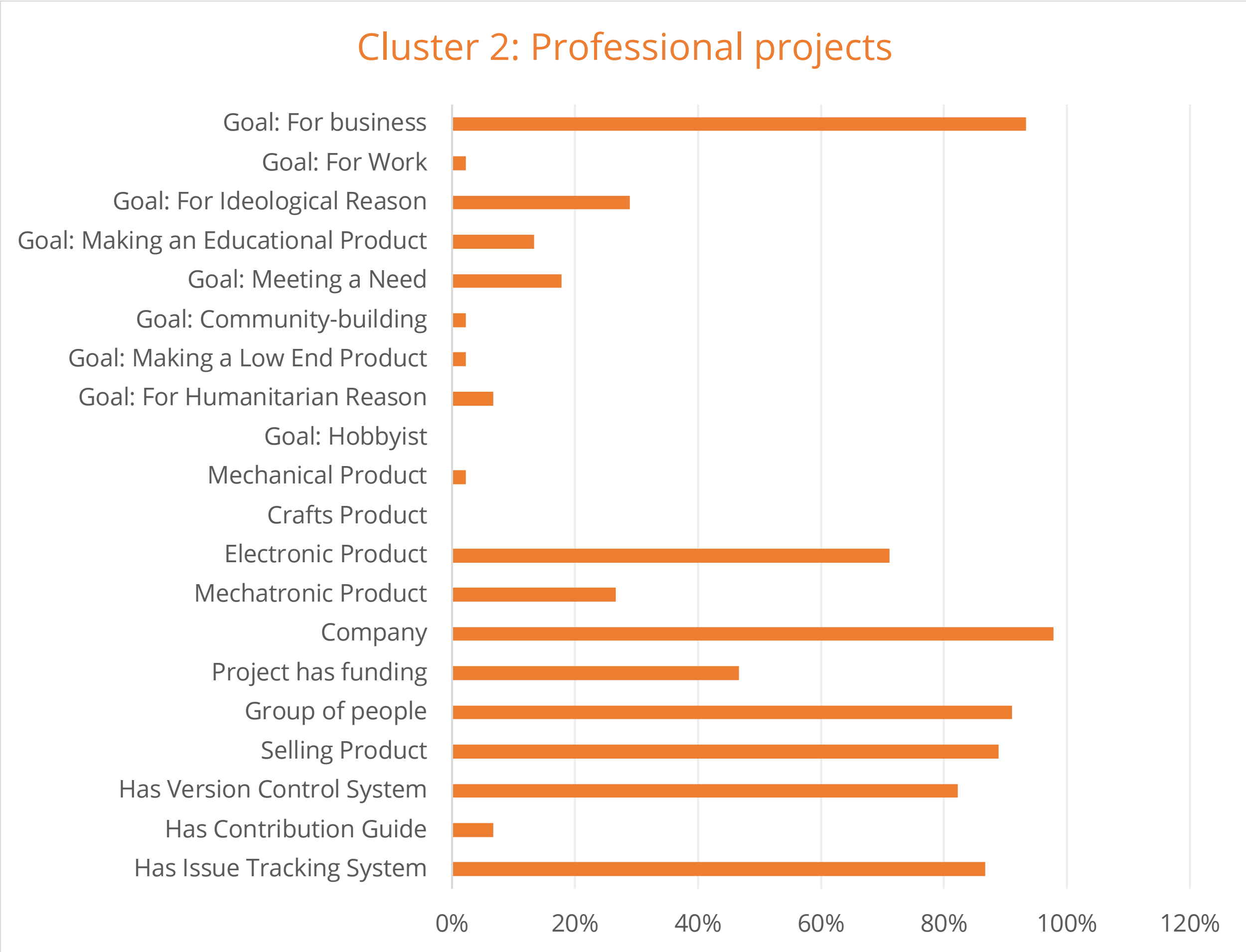

Figure 16: Composition of cluster 2.

In terms of goals, other than 'For business, 29% of the projects in cluster 2 have the goal 'For ideological reason'; 18% 'Meeting a need'; 13% 'Making an educational product'; 7% 'For humanitarian reason'; 2% 'Community-building'; 2% 'For work'; 2% 'Community-building'; 2% 'Making a low-end product'. Additionally, 82% and 87% of projects in cluster 2 have version control and issue tracking systems, respectively. Around 7% of projects in this cluster have a contribution guide.

It is also worth noting 71% of the projects in cluster 2 make electronic products, while 27% make mechatronic products and the remaining 2% make mechanical products.

3.7.3 Cluster 3: Unfunded projects

Figure 17 shows a bar graph illustrating the composition of cluster 3 in terms of the presence of each binary variable. To understand the dominating features of this cluster, we can observe the proportions of each variable. As in the previous cluster, we exclude the variables 'Has version control system' and 'Has issue tracking system' when looking at the dominating variables. From this graph, it can be seen that there is a variety of project goals present within the cluster: 53% 'For business', 50% 'Meeting a need'; 44%

'Making a low-end product'; 21% 'Hobbyist'; 15% 'Making an educational product; 12% 'For work'; 6% 'For humanitarian reason'; 3% 'For ideological reason; 3% 'Community-building'. Interestingly, it is also observed that none of the projects in this cluster has funding. For this reason, this cluster is given the name 'Unfunded projects'. It is worth noting that no *external* funding was identified – this means that the projects may still be self-funded from the originator(s), but this would not be possible to capture during data collection.

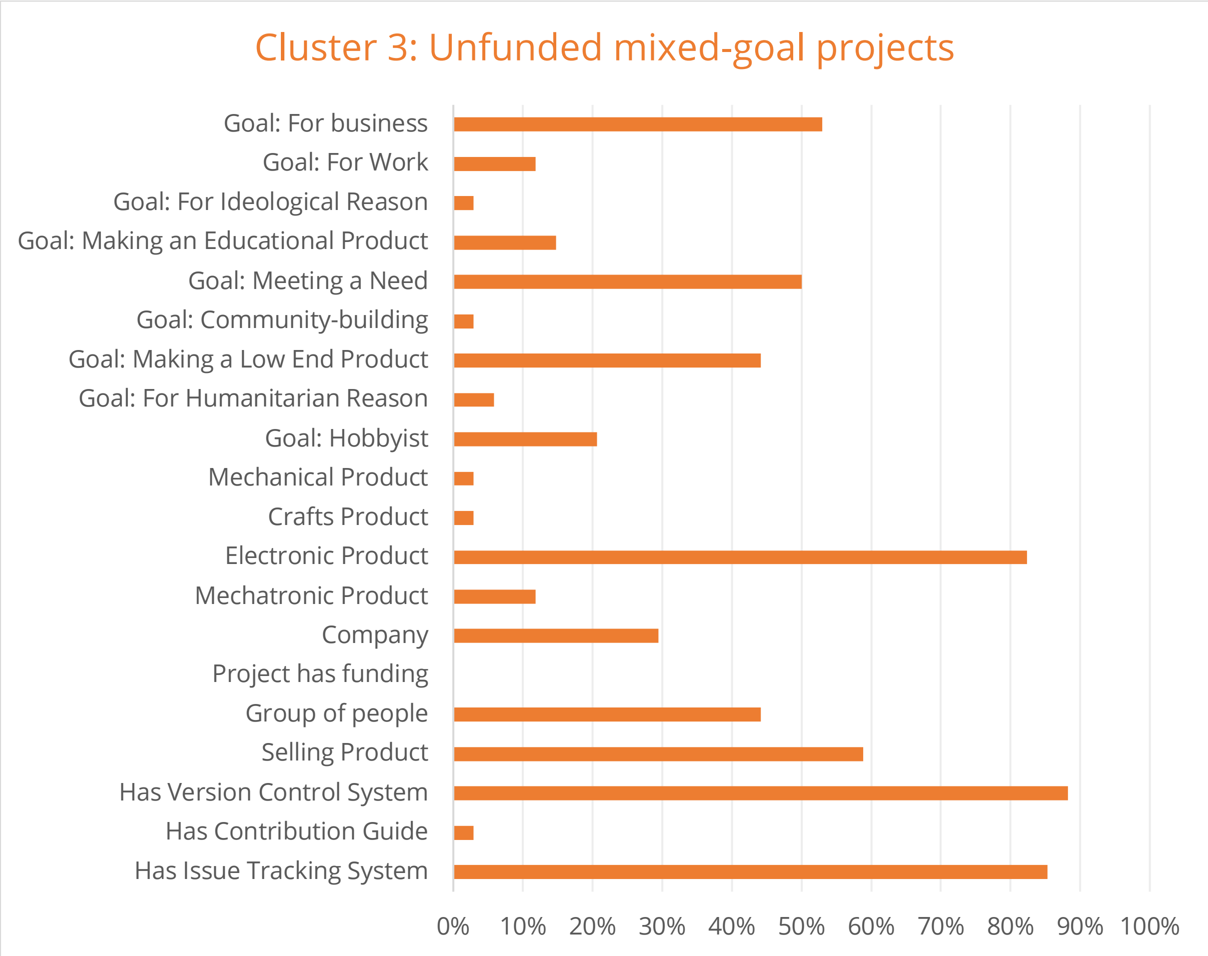

Figure 17: Composition of cluster 3.

In terms of domain, 82% of projects in this cluster make electronic products, 12% make mechatronic products, 3% make mechanical products, and 3% make crafts products. 59% of projects sell products, while 29% have a company. 44% of projects have a group of people contributing. Furthermore, 88% and 85% of projects in cluster 3 have version control and issue tracking systems, respectively. Around 3% of projects in this cluster have a contribution guide.

3.8 Robustness and implications of findings

So far, we have looked at the process and outcome of a typology study for OSHD projects using hierarchical cluster analysis. In the previous section (section 3.7) the three identified clusters were described. In this section, the robustness considerations of the clustering are described in section 3.8.1, while the implications of the findings are discussed in section 3.8.2.

3.8.1 Robustness considerations

This section reports on different considerations in terms of the robustness of the clustering, namely differentiation in section 3.8.1.1 and stability of the solution in section 3.8.1.2.

3.8.1.1 Differentiation

From the graph illustrated in Figure 14, showing the composition of the three clusters, it can be observed that there are substantial differences between the clusters in terms of the majority of variables. As such, we can give different descriptive names to each cluster, which summarise the unique features of the projects in each. The variables that show the least variation across clusters are the ones that are the swamping variables, as expected (see section 3.6.2).

3.8.1.2 Stability of cluster solution

Section 3.6.3 emphasised that the selection of the linkage algorithm and distance metric used for cluster analysis is important for generating a good cluster solution. In this section, the author addresses other factors which influence the stability of the cluster solution, such as the ordering of cases (IBM Corporation 2021b) and the cluster method used (Sarstedt and Mooi 2019; Van Ryzin 1995). This section addresses each one of these factors respectively for the final typology described in section 3.7.

Ordering of projects

It is a possibility that the ordering of the projects i.e., the rows in the dataset may affect the cluster solution (IBM Corporation 2021b). To ensure that the solution is stable, the ordering of the projects was randomised using Microsoft Excel[50]. This was done twice, to repeat the clustering 3 times in total. Figure 18, Figure 19, and Figure 20 show the distributions of the variables in clusters 1, 2 and 3 respectively after clustering using the three different orderings of the projects. From the graphs, we can see very little variation across the different cluster solutions for most variables, so from this perspective, we observe relative stability.

[50] The RAND function was used to generate a random decimal number between 0 and 1 for each case, i.e. row in the spreadsheet. Then, the RANK function was used to convert those to whole numbers from 1 to 100, following the method given in this website: https://trumpexcel.com/generate-random-numbers-excel/. Then, the rows were placed in ascending order according to this newly generated number. This resulted in a new randomised order of cases.

The variables for which we see a little bit higher variation are the *Goal: Hobbyist* in cluster 1, and *Goal: Meeting a need* in cluster 3. The variable *Goal: Hobbyist* is 19% less when clustering using random order 1 compared to the original order. While it is a defining variable for cluster 1, it would not affect the cluster solution because it still is present in a very high proportion compared to other variables in the cluster. The variable *Goal: Meeting a need* is present in 100% of projects in cluster 1using random order 1, compared to 50% using the original order. This is a more significant difference since this could potentially shift the defining feature of the cluster as no longer having mixed goals but rather dominated by 'Meeting a need'. Random order 2 however results in less of a difference than the original order, so this provides some evidence for the original feature of having a variety of goals. Further repetitions and using data from more projects could help address this issue.

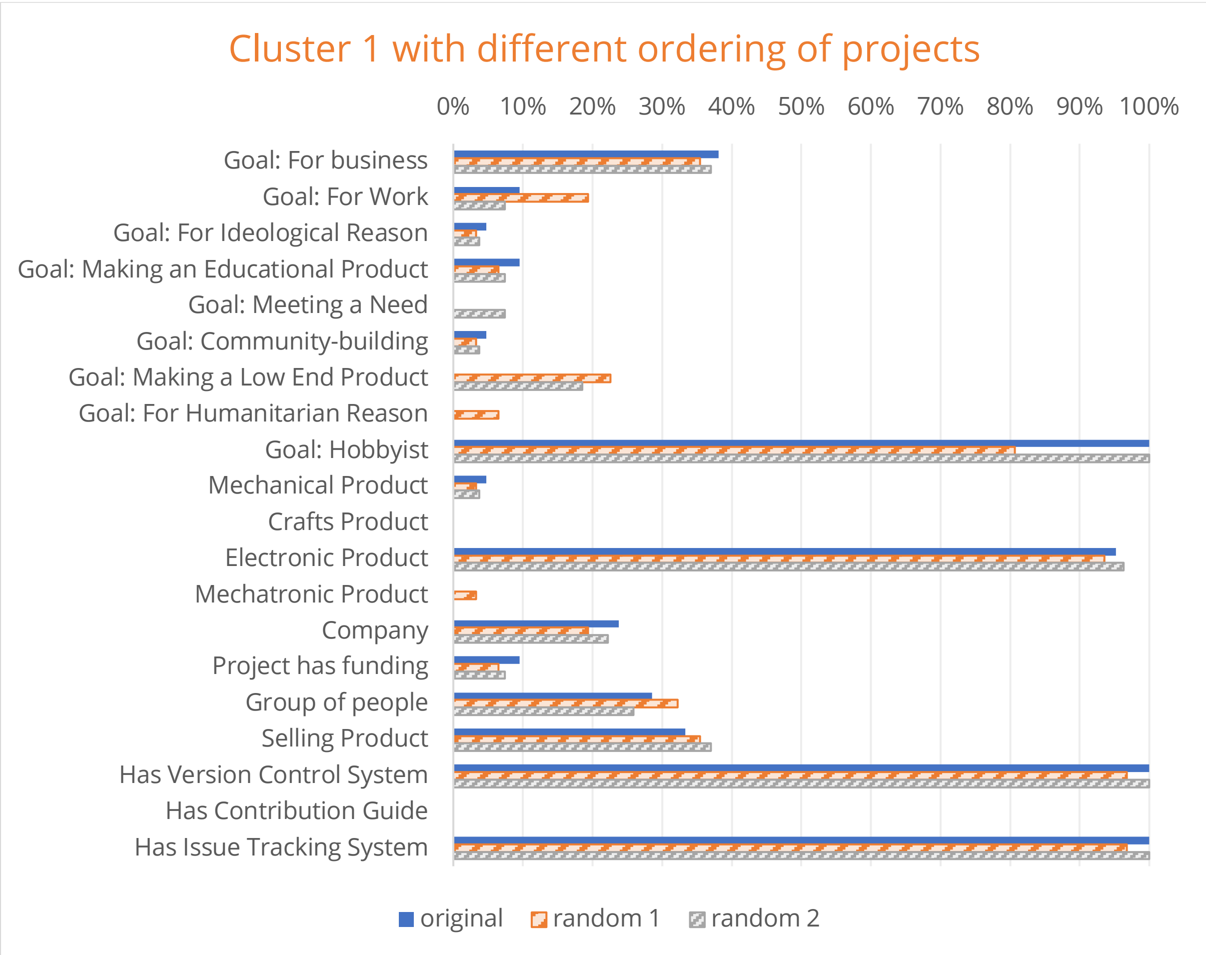

Figure 18: Cluster 1 with different ordering of projects

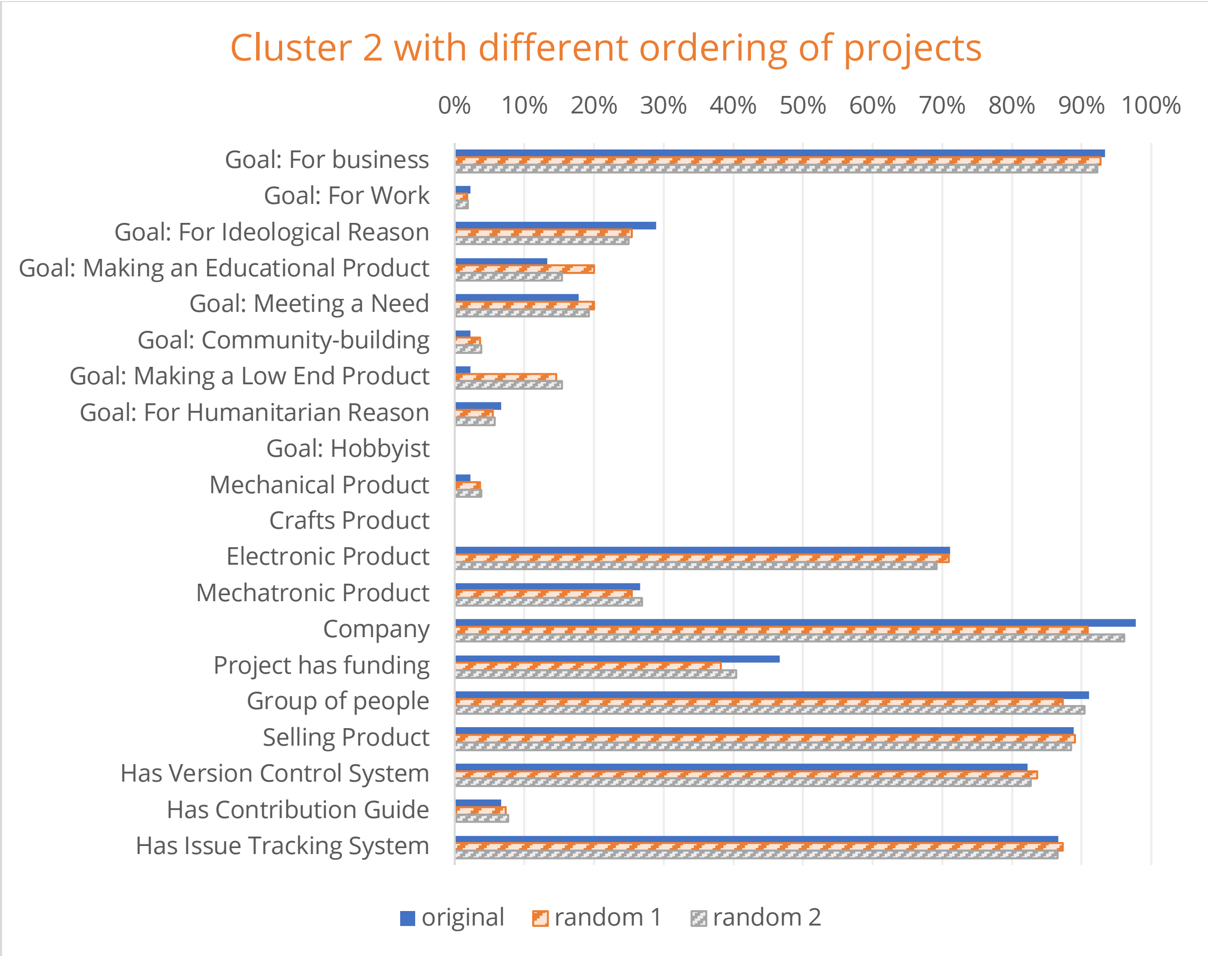

Figure 19: Cluster 2 with different ordering of projects.

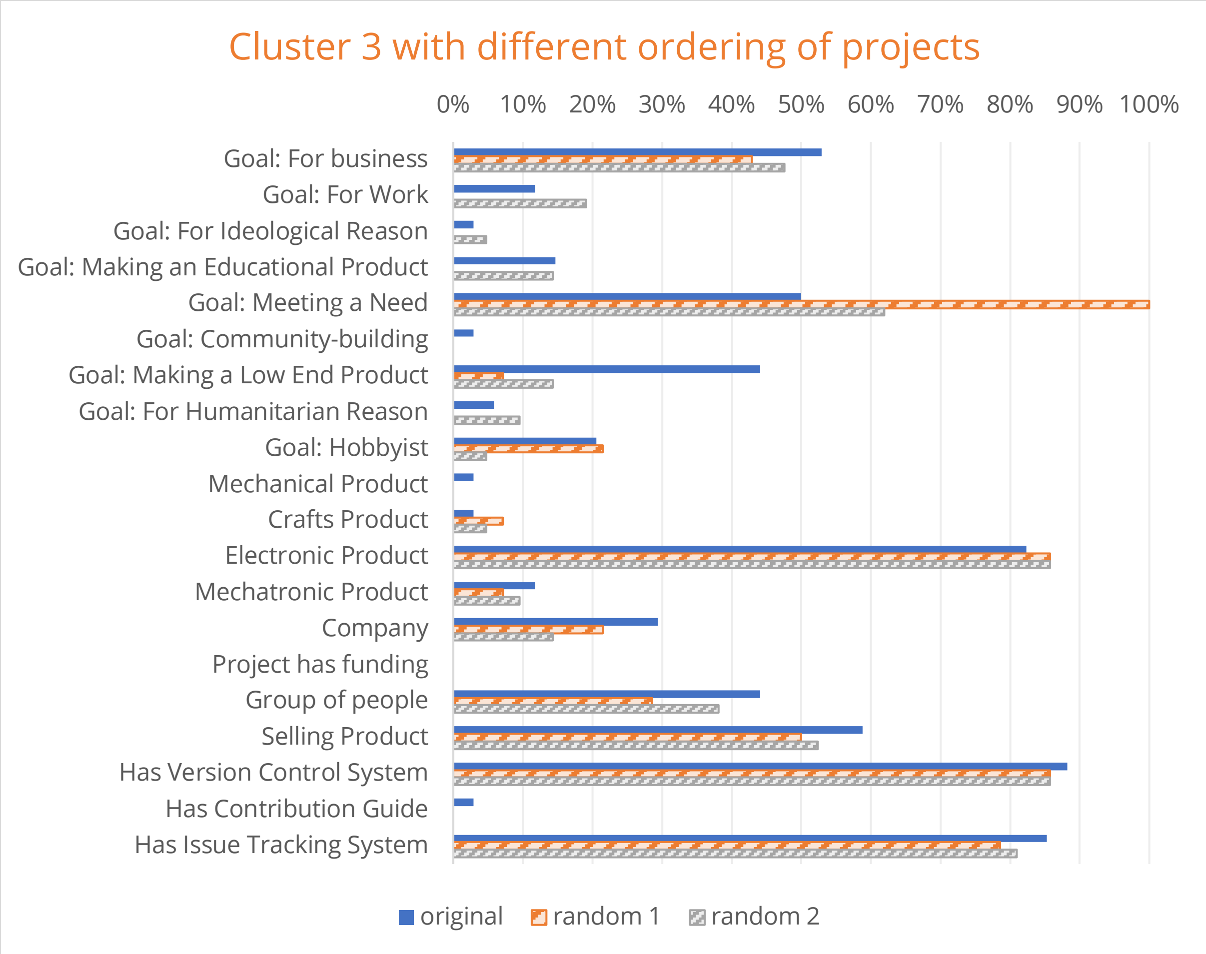

Figure 20: Cluster 3 with different ordering of projects.

Cluster methods

Employing different cluster methods and comparing the cluster solutions is another way to check for stability (Sarstedt and Mooi 2019). To obtain the result described in the previous sections, the hierarchical clustering method was used. To check for stability, the author employed also K-means clustering. Figure 21, Figure 22, and Figure 23 show the variable compositions of each cluster 1, 2 and 3 respectively when employing hierarchical (in the original ordering of projects) and K-means clustering (also in the original ordering). We observe that all the clusters show relatively substantial differences, particularly in the latter. Therefore, the solution is not so stable when it comes to employing different cluster methods.

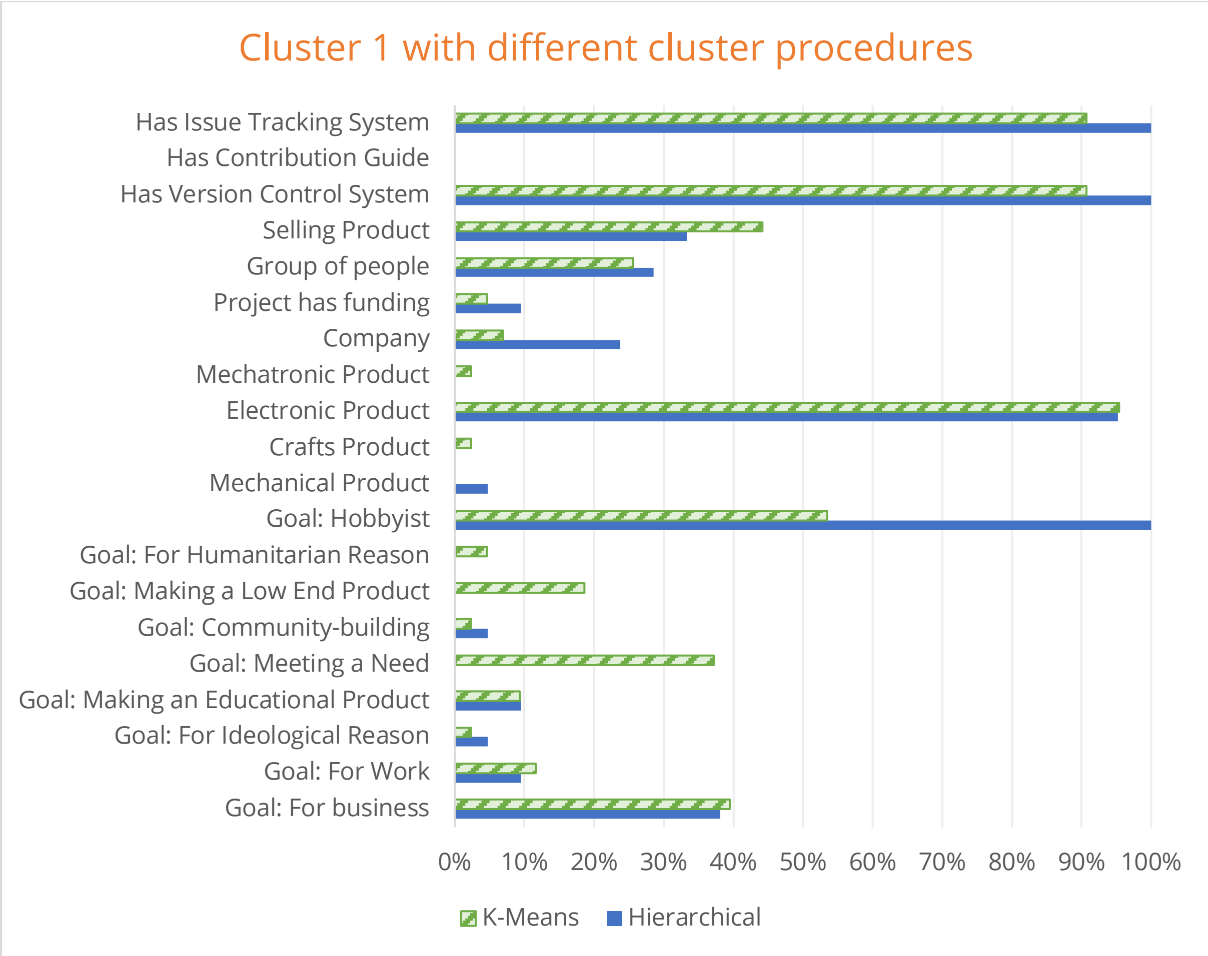

Figure 21: Cluster 1 comparison between hierarchical and K-means clustering.

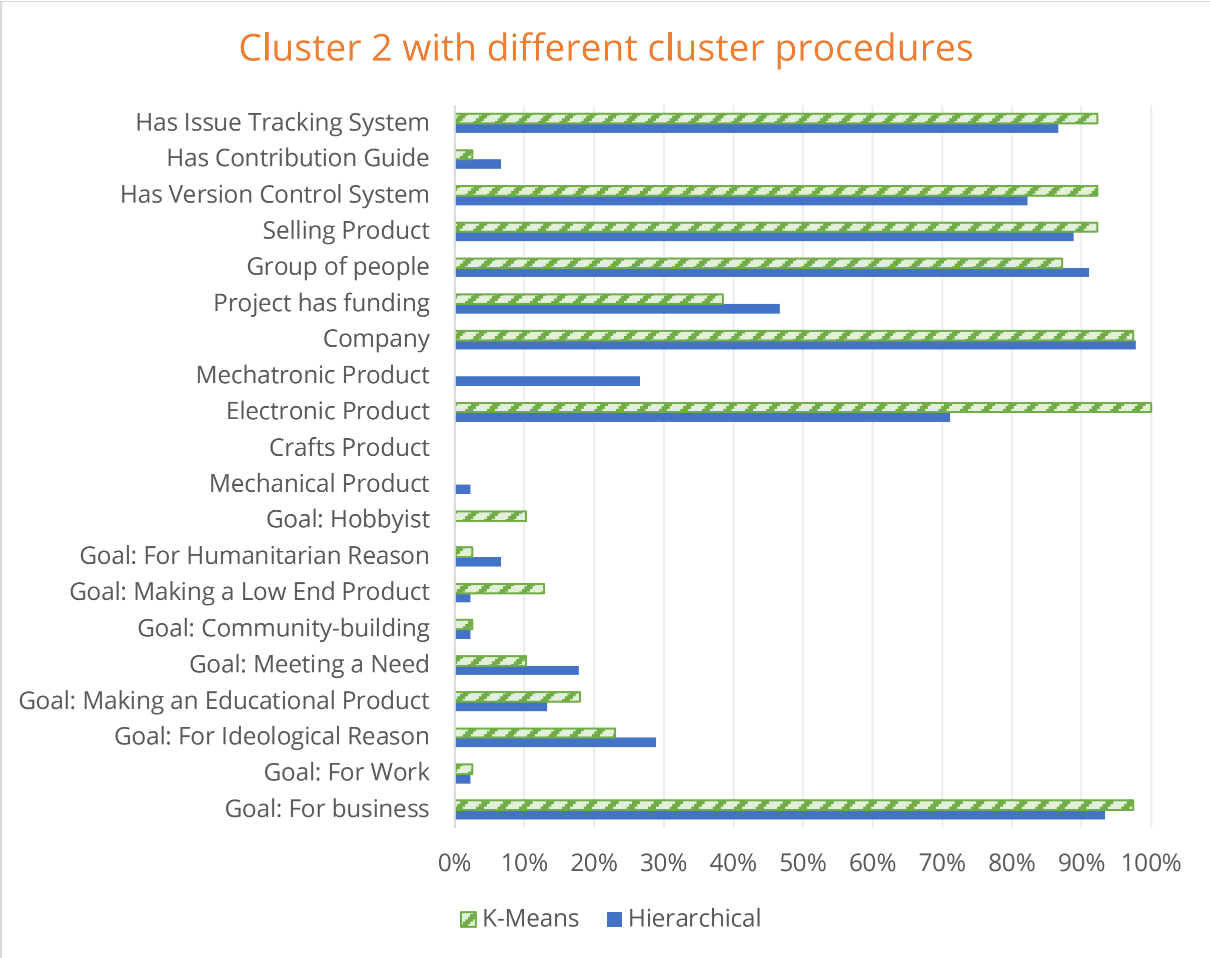

Figure 22: Cluster 2 comparison between hierarchical and K-means clustering.

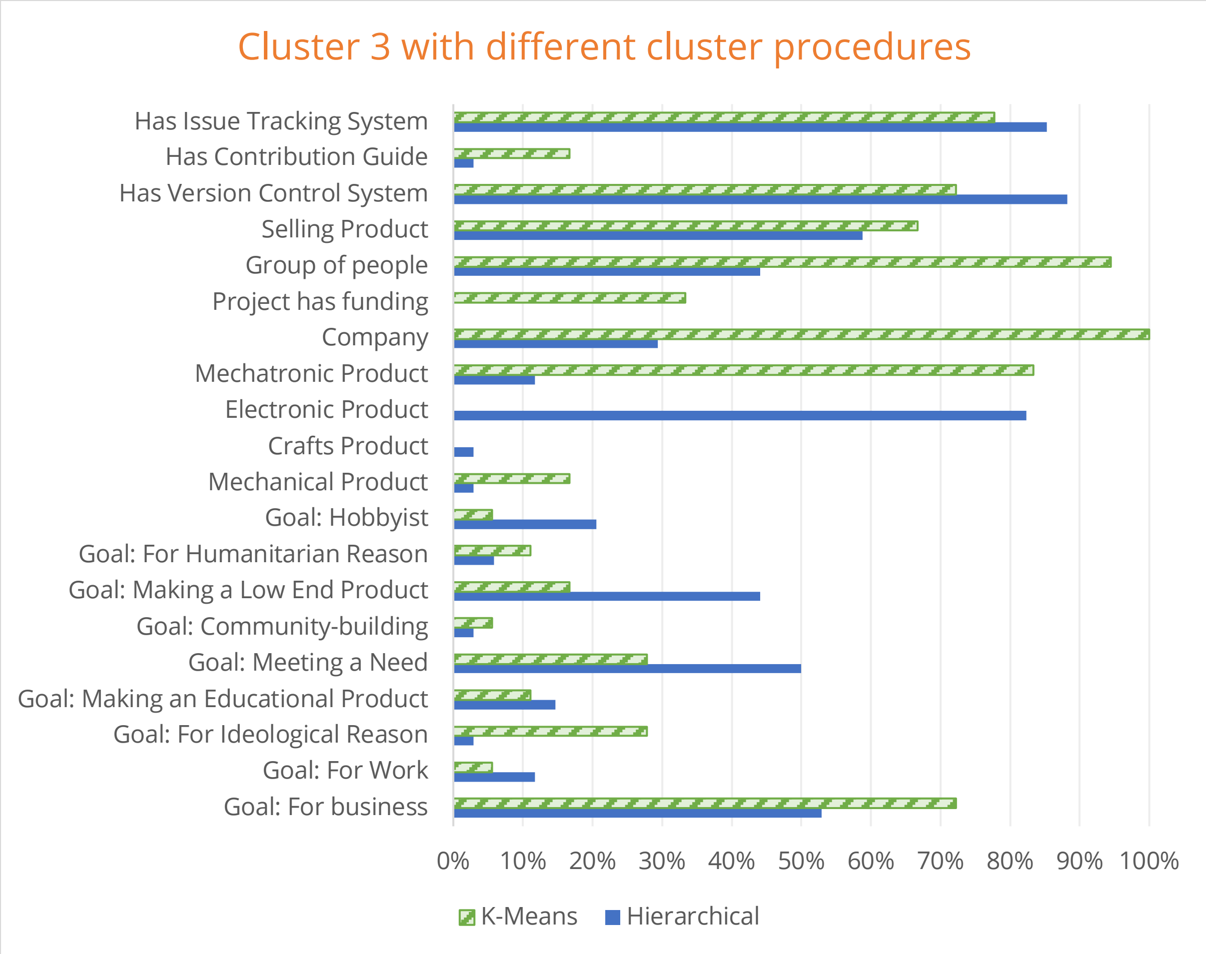

Figure 23: Cluster 3 comparison between hierarchical and K-means clustering.

3.8.2 Implications of findings

Three distinct project types were uncovered in this study. This section compares and contrasts the project types in terms of the variables used and discusses implications in conjunction with relevant literature.

3.8.2.1 Project goals

Baccarini's (1999) seminal article "The Logical Framework Method for Defining Project Success" breaks down success into product success and project management success. The former is concerned with project goals, while the latter is with inputs and outputs. He states that project management success is subordinate to project success. This is illustrated by the following statement from de Wit (1988): "This explains why projects which ought to be considered a disaster in project management terms are perceived as successes, simply because the higher-level objective was met". From this, we can infer that reaching project goals or objectives is one, if not the, most important aspect of project success. Therefore, if we want to create a typology of OSHD projects to be used for creating best practices for projects, we can safely assume that the first place to look is at project goals.

It is important to note at this point, that various seemingly synonymous words like 'goals', 'purpose' and 'objectives' can take on different meanings, and therefore must be defined. The literature does not appear to have a consensus on this. Baccarini (1999) mentions that project purpose relates to the product's 'fitness for use', while project goal relates to the strategic objectives of the enterprise. When we refer to project goals in this study, we follow Baccarini's (1999) definition.

When asking the question "what kinds of goals do OSHD projects have?" one may choose to consult with experts and/or analyse the literature. For this study, the author did both. A consultation with three experts in the field of OSHD not only confirmed that project goals relate to project success, but that they are also a differentiating factor for segmenting projects into categories. Project goals was the most frequently quoted theme in the expert interviews when asked about what factors differentiate OSHD projects from each other. Project goals were indeed found to be a differentiating characteristic for the typology through cluster analysis.

Comparing the goals across the different project types, shown in Figure 24, it can be seen that most goals are present in at least a small proportion in all the clusters, except for 'Hobbyist', 'for Humanitarian reason' and 'Making a low-end product'. Note here that the goal variables were not mutually exclusive – each project could have up to three goals (as previously explained in section 3.5.1 Table 13).

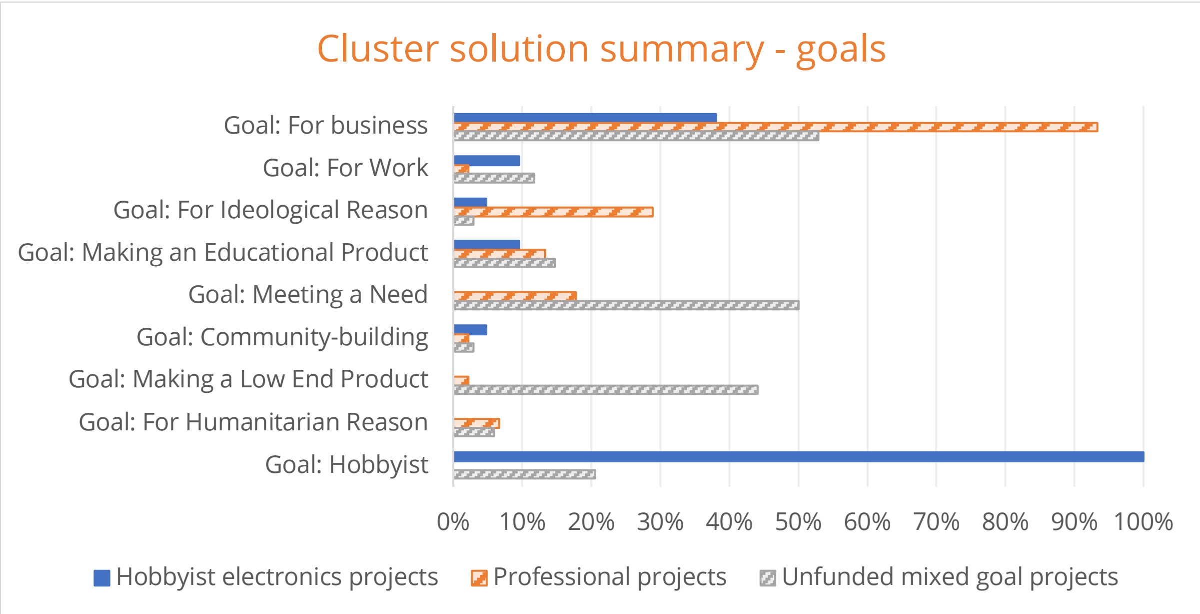

Figure 24: Percentage of different goals across each project type.

All projects in project type 1 had the goal 'hobbyist', while none of the projects in type 2 had that goal. This is in line with the idea that the second project type was called 'professional projects'. While 38% of projects in type 1 also had 'for business' as a goal, the main difference was that those projects usually sold products on online maker marketplaces, such as Tindie[51], in small batches created by the hobbyist project originator(s). By contrast, 93% of projects in type 2 had 'for business' as a goal and often had professional websites and sold their products themselves straight to the consumer. 53% of projects in type 3 also had 'for business' as a goal, and we observe a mix of types of sales. Project type 3 also contained 21% of projects with the goal 'hobbyist'.

Hausberg and Spaeth (2020) identified "own-use value" as a motivation to participate in OSHD projects. This refers to the value a product has for fulfilling a need of an individual who participates in the project. While this is not that obvious for paid employees which participate in OSHD projects, von Hippel (2001) poses the majority of people working without any monetary compensation on open source projects are also users of the developed product. Therefore, one could logically conclude that the own-use value is potentially a strong motivation to participate in or create an OSHD project (Hausberg and Spaeth 2020). This has been confirmed in several studies of OSS participants who report that own-use value could be a motivation to contribute to a project (Lakhani and Von Hippel 2003; Ghosh 2005; Lakhani and Wolf 2007). This is not expressly reflected in the goals, but it is captured sometimes through 'meeting a need' if the own-use value was expressly referred to in the project's online presence. It could also potentially be captured under the goal 'hobbyist' too since it is suspected many hobbyist projects are driven by own-use value, but if that was not expressly stated on the project's online presence then the author did not log 'meeting a need' as a goal.

Distinguishing type 3 from the other two types in terms of goals is a little bit more complicated. This cluster is the only one which had all the goals present to some degree. Around half of the projects in this cluster had 'for business' and 'for meeting a need' as a goal. It is important to note at this point that logically, meeting some kind of need is in principle a goal for all projects. In other words, all projects start for some reason, whether that may be just for fun, or wanting to change the world. For the goal 'meeting a need' here, the author used it to term projects which explicitly stated that they identified a need in the world (or in their personal life as mentioned in the previous paragraph) that they wanted to fulfil, for which no other existing product could fully meet. This cluster captured most 'meeting a need' projects, and most 'making a low-end product' projects.

3.8.2.2 Domain

Figure 25 shows the different domains of the projects within each type. The domain variables were mutually exclusive. The three project types had similar percentages of mechanical products. Type 3 was the only type which included crafts products. Types 2 and 3 were the only types containing mechatronic products, with type 2 having the majority percentage. The author hypotheses that the reason why professional projects had the highest percentage of mechatronic projects could be attributed to the fact that these types of products tend to be more complex – therefore, it is more likely that they

[51] https://www.tindie.com/

require (a) a group of people to develop them (b) the willingness/ability to sell them because they require more time to be developed as they are more complex. All project types had at least 71% electronics projects. Type 1 projects comprised 95% electronics, hence the chosen name 'hobbyist electronics'.

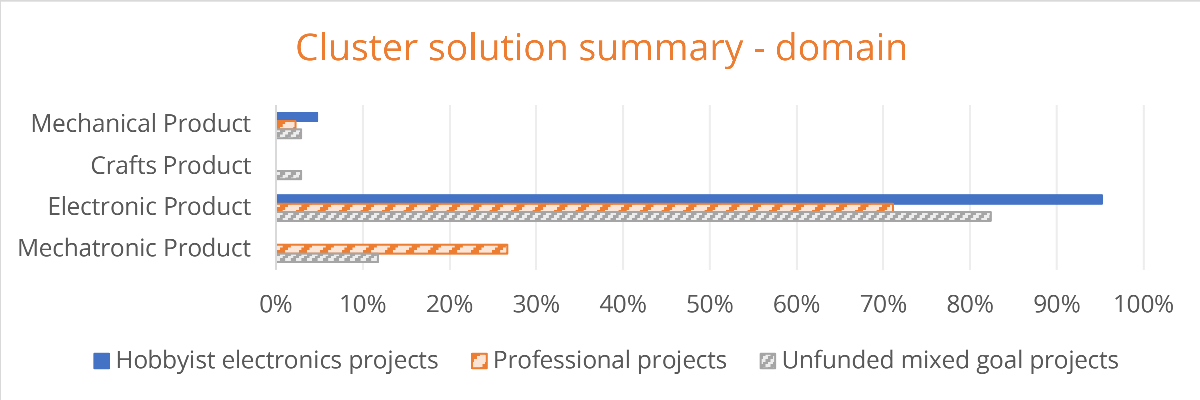

Figure 25: Percentage of projects of each domain across the three project types.

Most projects, in general, were electronics projects. This is interesting in itself, as it hints at a number of underlying reasons. First, a possible bias in the sampling – perhaps the OSHWA certification programme is more known/more popular within electronics communities or it is more important for electronics projects to be certified. This could be because the word 'hardware' is often associated with electronics hardware, such as computers, PCBs, and accessories. This is well illustrated by the Cambridge English Dictionary (HARDWARE | meaning, definition in Cambridge English Dictionary n.d.), where the first definition of hardware given is: "the physical and electronic parts of a computer, rather than the instructions it follows". This illustrates the point that hardware is often contextualised as opposed to software. However, in the case of OSH, while the word hardware is used, it is interpreted to mean physical products. These could indeed be electronics products, but they could also include robots, lamps, and tables, to name a few.

Other than a bias in the sampling, the high number of electronics products could potentially be because there are more electronics OSHD projects than other types of projects. If this is the case, an explanation could be that since the open source movement initially started from software, which involves computers, it follows logically that the next step would be for the open source movement to spread out to electronics hardware, which are associated with computers, before the movement is able to spread out into other types of products.

3.8.2.3 Company

All three project types contained projects which had a company associated with them. This is shown in the bar graph in Figure 26.

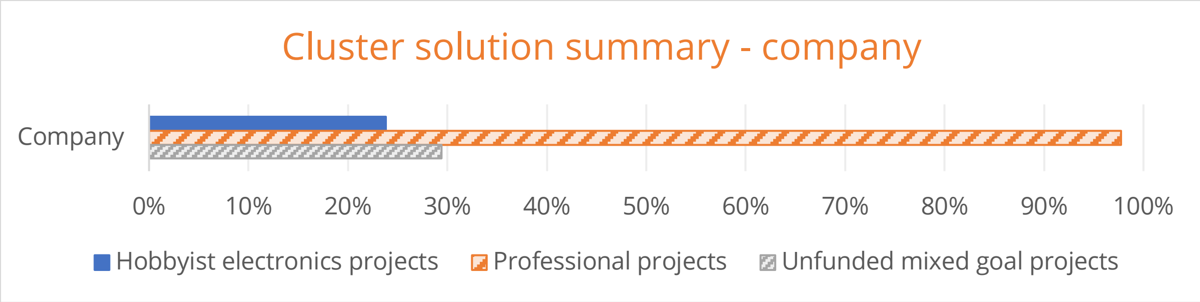

Figure 26: Percentage of projects across each type which had a company associated with them.

98% of projects in type 2 have a company. This is one of the key reasons why the name ‘professional projects’ was ascribed to this type. 29% of type 3 projects have a company, while 24% of type 1of projects have a company. It is difficult to say to what extent having a company influences success, for example, but it can be logically derived that having a company means a project is more professional, has a high capability of conducting and coordinating sales, and can employ people.

3.8.2.4 Funding

Lack of funding was a distinguishing characteristic of project type 3, while 47% of projects in type 2 have funding and only 10% (only 2 projects) of type 1. This is illustrated in Figure 27. Interestingly, the majority of funded projects are those in type 2. Perhaps this is because having a lot of sales can attract investment in the company, which was seen in some of the projects analysed. Another type of funding included crowdfunding campaigns and a company is publicly traded (the fact that the public can buy stocks in the company means that funding is injected into the company and could thus potentially go to that project).

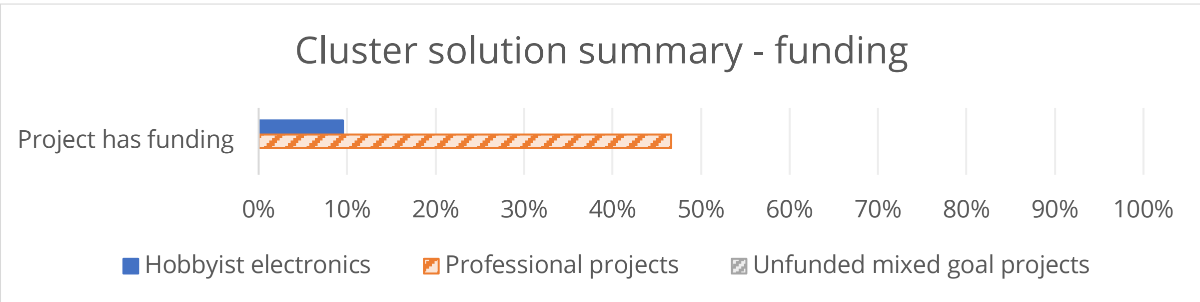

Figure 27: Funding in the different project types.

In a previous study by the author, presented in section 2 it was found that OSHD practitioners consider that having funding is characteristic of successful projects (Antoniou et al. 2022). In that sense, type 2 projects are the most successful.

3.8.2.5 Group vs. solo contributors

Figure 28 shows the percentage of projects which had a group (i.e., more than 1) of contributors participating. All project types contained some level of group projects.

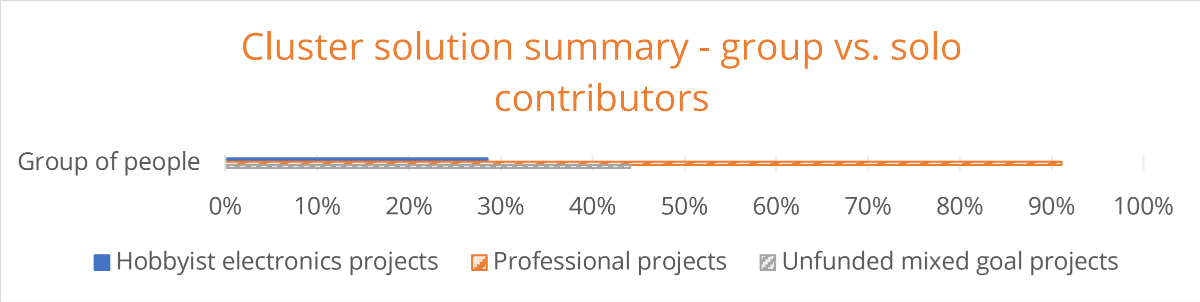

Figure 28: Percentage of projects which had a group (i.e., more than 1) of contributors.

Most (91%) of professional projects (type 2) were found to have a group of contributors. This could potentially be because these projects are 'professional', they generate revenue through sales, often have a company associated with them, and could therefore either (a) employ people and pay them for their time (b) be popular. Both of these factors increase the probability of having more than one contributor. Only 29% of hobbyist electronics projects had more than one contributor. This could potentially be because a lot of these projects are started by makers and were usually DIY-style projects which may mean that not many people know about the project, reducing the likelihood of new people contributing. 44% of unfunded projects were group projects. It is difficult to explain what the reason could be for this, or what implications this could have.

In a previous study by the author (Antoniou et al. 2022), presented in section 2, having multiple contributors in a project is an indicator of success. The number of contributors could also be indicative of how successful a project is. In that sense, project type 2 may include more successful projects because it has more group projects.

Linking back to the project archetypes 'isolated innovator' and 'development community' identified by Bonvoisin et al. (2017), the author observed both types of projects during data collection. Many of the projects which were 'solo' or 'isolated innovator' fell under type 1 and some under type 2. These projects were often low-complexity electronics products such as PCBs. They were often unfunded and were done just for fun or to fuel the individual's electronics hobby. They often did not sell products, but if they did they were in small batches on maker marketplace websites such as Tindie. This type of project is typical of type 1. Regarding 'projects fitting the 'development community' archetype, the author did identify a few examples. These were usually in type 2. However, a project having the variable 'group' does not necessarily mean that it is a development community. This is because the latter implies a large group of people participating, while the former just means more than 1 person.

3.8.2.6 Selling products

Figure 29 illustrates a bar graph showing the percentage of projects which involved selling products. All project types contained some projects selling products.

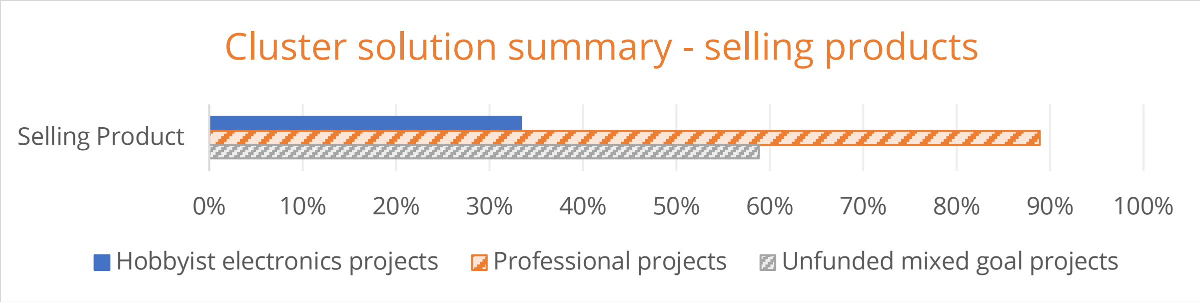

Figure 29: Percentage of projects selling products across the three project types.

89% of projects in type 2 have sold products. This is to be expected of these 'professional' projects as they are characterised by business and sales. 59% of unfunded projects also had sales. This is perhaps because the main differentiation between the two types is that type 2 projects are more simply oriented towards business – they seem to want to do business for business' sake, i.e., to make money, while type 3 projects are usually underpinned by an additional motivation, which is perhaps more mission-driven, such as creating a low-end product (to provide access to that product/technology to people which may not have had it before due to financial constraints). Hobbyist electronics projects also had sales sometimes, and these were mostly in small batches, on maker marketplaces.

In a previous study by the author (Antoniou et al. 2022), presented in section 2, it was found that selling products is a characteristic of successful OSHD projects. In this sense, type 2 projects are more successful than the other two types.

3.8.2.7 Openness (version control, contribution guides, issue tracking)

As mentioned in section 3.5.1 Table 13, the process openness criteria 'presence of version control system', 'presence of contribution guide', and 'presence of issue tracking system' identified by Bonvoisin and Mies (2018) were used for assessing the openness of the analysed projects. The 5 product openness criteria they identified are already present in all projects as they are requirements for certification by OSHWA. Figure 30 shows the percentage of projects having each of these criteria in each project type.

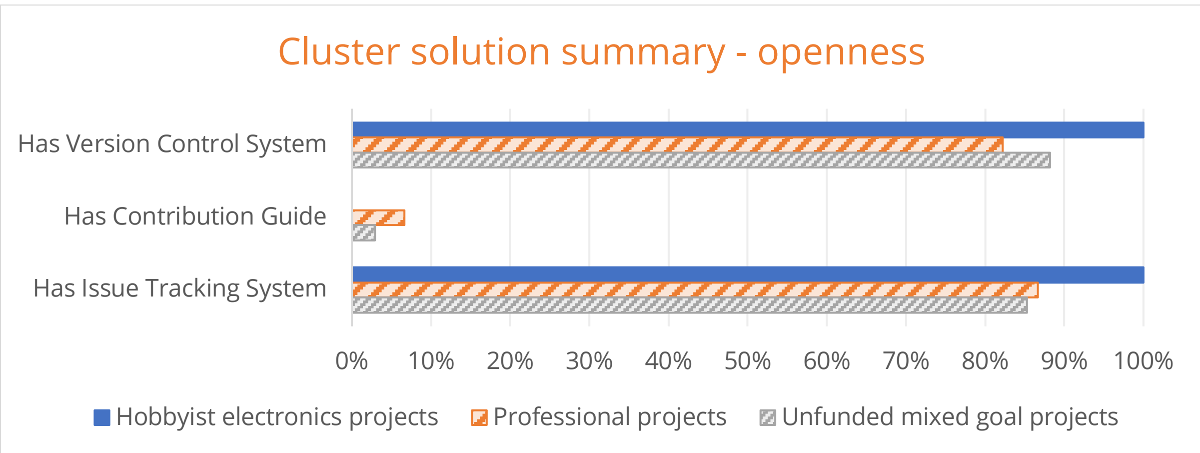

Figure 30: Openness across the three project types.

It is observed that, in general, the majority of projects score highly on openness in terms of the usage of a version control system and an issue tracking system. In particular, type 1 projects have these two features. Very few projects, however, have a contribution guide. No type 1 projects have contribution guides, while 7% and 3% of type 2 and type 3 projects respectively have contribution guides. It is difficult to assess these variations since they are so small. In terms of project success, in a previous study carried out by the author and presented in section 2, it was found that projects which are more open are more successful in the eyes of OSHD practitioners. It is difficult to say if any type is more open that the other based exclusively on these process openness criteria.

3.9 Conclusions, limitations, and future work suggestions

In this section, the researcher summarises the learnings drawn from this study and discusses its limitations, offering future work suggestions for tackling them.

3.9.1 Conclusions

This section presented a typology of OSHD projects, along with a detailed overview of the steps taken to create it. The typology of OSHD projects presented here consists of three project types, represented by the clusters drawn from hierarchical cluster analysis using Ward's Linkage and the Squared Euclidean distance metric. Project type 1 was labelled 'Hobbyist electronics': these were electronics OSHD projects that were typically carried out by people who do OSHD as a hobby. Type 2 was called 'Professional projects': projects which were characterised by having a company, a group of people working together and selling products. Type 3 'Unfunded projects' included projects which did not have external funding, as well as a mix of different goals. Each type appeared to be quite different from the others in terms of its defining characteristics, and the solution appeared relatively stable when carrying out the clustering using different random ordering of cases, increasing confidence in the quality of the method.

In addition, this study helps advance the OSHD field in numerous ways. It presents learnings which characteristics are relevant for creating a typology, through literature review, expert interviews and methodological constraints. It also provides a methodological foundation for not only generating project types based on similarities and differences (which could be used in future studies in the field of OSHD or even other fields), but also for potentially adapting processes and tools to projects and developing tailored guidance to projects such as success indicators, metrics and best practices, based on their unique context and features.

To sum up, this study is a first step in empirically identifying the different types of OSHD projects (the overarching research question) and provides a solid foundation for exploring the possibility of using it to inform best practice guidelines. This will be investigated in section 4. The following section 3.9.2 presents the limitations of this study and suggests possible future work which could help address them.

3.9.2 Limitations and future work suggestions

Like all research endeavours, this study is not without its limitations. We explore sampling and stability limitations in the following two sections, 0 and 0 respectively. Later, section 3.9.2.3 suggests future work based on temporal observations of OSHD projects.

3.9.2.1 Sampling

By studying projects which have generated certified OSH, we have only looked at projects of a relatively high 'maturity', meaning they have been able to produce at least a working prototype which can comply with the OSHWA OSH definition in order to be certified. Specifically, they have design files published under an open source license. This means that OSHD projects which are at earlier stages of product development –

i.e., ideation – are not included. However, this also means that the projects under study have been successful in developing at least a first prototype and 'surviving' the early stages of development, which is an indicator of success (Antoniou et al. 2022). This could be potentially analogous to the 'survival' of start-ups (Gartner et al. 1999), without which a project would not be able to continue running and fulfil its goals.

In terms of sample size, there is no consensus in the literature as to a widely accepted guideline for sample size versus number of clustering variables (Sarstedt and Mooi 2019). Dolnicar et al. (2016) investigate the effect of different sample sizes on market segmentation, and they warn that insufficient sample sizes can result in suboptimal results. They found that an increase in the sample size to clustering variable ratio from 10:1 to 30:1 significantly improves the validity of the clustering solution. They go on to say that while this improvement levels off as the ratio increases, it is still noticeable up to a ratio of 100:1. In this study the sample size to clustering variable ratio was approximately 11:1[52]. This suggests that a cluster analysis performed with a higher sample size may lead to a different, better clustering solution. This provides an interesting and feasible avenue for future work, using the data collection methodology outlined in this section.

Ideally, however, the entire population of OSHD projects certified by OSHWA would be analysed. This way, we could know that the clustering solution fully represents the entirety of the population of certified projects, thus removing sample representativeness issues. However, it must be noted that an unknown number of OSHD projects which are not certified by OSHWA may exist, which is not possible to estimate at this point in time as they are scattered across the internet on websites like GitHub[53], GitLab[54], Wikifactory[55] and more. This means that even if cluster analysis is performed on the entire database of OSHWA-certified projects, it cannot be claimed that the clustering solution is representative of the entire population of OSHD projects in the world. It would, however, be a good starting point since it captures a large amount of OSHWA-certified projects.

3.9.2.2 Cluster solution stability

It was observed that the cluster solution is relatively stable concerning the ordering of the projects in the dataset. However, it was not so stable when employing a different clustering method – K-means clustering. It was also not particularly stable in terms of using different linkage algorithms and distance measures. This is perhaps due to the limitation of the sample size. A larger, representative sample of the population of OSHD projects should theoretically yield better stability in terms of this. However, it must be noted that the different linkage algorithms have varying levels of sensitivity to different phenomena, such as outliers (see Table 17). In the experience of this author when

[52] 100 projects clustered using 9 variables.
[53] https://github.com/
[54] https://about.gitlab.com/
[55] https://wikifactory.com/

performing the analysis, using different linkage algorithms produces different solutions, but using the same linkage algorithm with different distance measures tends to produce similar solutions. It is also worth noting that, according to Sarstedt & Mooi (2019), it is a common occurrence for the cluster solution to change, even when the solution is adequate. It is also possible that if the cluster centres produced using Ward's linkage using hierarchical clustering are inputted for the starting partition of K-means clustering, a more similar solution may be found (Sarstedt and Mooi 2019). This was not performed in this study due to time constraints and could be employed in future studies.

3.9.2.3 Temporal observation of OSHD

An important avenue for future work would also include temporal observation of OSHD. This could be done using two different perspectives.

First, this could be done by employing the method of creating a typology of OSHD projects in this study at different periods e.g., every 1 year for 5 or more years, for the same sample of projects. This could help provide insights as to how projects evolve, whether their characteristics change and whether the observed types change. It could also provide insights as to whether projects tend to follow a particular evolution in terms of their type over time and could inspire new research questions and further studies.

The second way this temporal aspect can be employed would be to employ the methodology given in this study every set number of years, e.g., every 5 years, for a different data set of projects. This could provide insights as to whether the OSHD field itself is evolving and whether different types of projects or different numbers of projects within the different types exist. Having typologies which were created at different points in time would provide an interesting point of comparison for the evolution of the OSHD field.

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Section 4. Understanding replicability in OSHD projects

4.1 Prologue

So far, this thesis has shed light on the breadth of OSHD projects. In section 2, the characterisation of project success in OSH projects through the perspective of practitioners was presented. Then, section 3 presented a classification of OSH projects into types. The resulting outcome was three types of OSH projects: hobbyist electronics projects; professional projects; and unfunded projects. Both of these studies looked at the variety of projects and attempted to make some broad generalisations of the projects in the field.

This section presents a study which aims to explore the depth of the OSHD phenomenon by delving deep into a core concept of openness: hardware replicability. By researching replicability, we investigate the ability for someone who was not a participant in the development of an OSH to build that OSH at their location using materials they obtain. Replicability is different to repeatability, because the latter relates to the ability of original OSH developers to re-build that OSH again. It is also different from reproducibility, because that relates to the ability of an individual who was not one of the original OSH developers to build the same hardware but without using the source shared by the original OSHD developers.

Replicability, as noted throughout this thesis, is one of the three aspects of openness, along with transparency and accessibility, as identified by Balka et al. (2014). This is because replicability relates to the possibility for someone to replicate a hardware based on the source shared by the original hardware developers. Repeatability and reproducibility are not relevant because they do not relate to both an external individual and the same source, and, by extension, openness.

Understanding the replicability of hardware can also help us understand openness, the most fundamental aspect of OSHD which sets it apart from its closed source counterpart. Additionally, replicability of OSH was identified as a characteristic of successful projects in section 2 of this thesis.

The study given in this section is presented via a paper (henceforth referred to as 'paper B)' published by the researcher at the International Conference on Engineering Design 2021 (ICED21), in a collaboration with colleagues in the OPENNEXT project from the University of Grenoble Alpes. In section 4.2 a declaration of authorship is given, explicating the author's contribution to this study.

Paper B investigates the following hypothesis:

Hypothesis: the assembly instructions and the bill of materials are necessary but not sufficient conditions to replicate an OSH.

Although the paper structures itself around this hypothesis, it delivers answers to the following research questions implicitly:

RQ1: what are the factors affecting the replicability of OSH?

RQ2: what are the steps involved in replicating an OSH? This study maps the replication process in the form of a flowchart.

RQ3: what project practices can be suggested for increasing the replicability of an OSH? Such practices could be developed using the factors identified by addressing RQ1.

This study is a first and unique attempt to identify a list of the factors affecting the replicability of OSH, as well as create a flowchart of the OSH replication process. It uses learnings from the survey data presented in this thesis in section 2 in combination with learnings from interviews with OSHD practitioners that the collaborators from the University of Grenoble Alpes undertook, in order to synthesise advice targeted towards OSH practitioners regarding how they can increase the replicability of the OSH they develop.

In section 4.4, we take paper B's findings a step further by investigating whether new insights can be developed by looking at whether practices for improving replicability in OSHD projects can be adapted based on the project types identified in Section 3.

4.2 Declaration of authorship

This declaration concerns the article entitled:	
"Identifying the Factors Affecting the Replicability of Open Source Hardware Designs"	
Publication status	
Draft manuscript [ ] Submitted [ ] In review [ ] Accepted [ ] Published [x]	
Publication details (reference)	Antoniou, R, Pinquié, R, Boujut, J-F, Ezoji, A & Dekoninck, E 2021, 'Identifying the Factors Affecting the Replicability of Open Source Hardware Designs', Proceedings of the Design Society, vol. 1, pp. 1817-1826. https://doi.org/10.1017/pds.2021.443 [Distributed under CC BY-NC-ND licence]
Copyright status	
I hold the copyright for this material [x]	Copyright is retained by the publisher, but I have been given permission to replicate the material here [ ]
Candidate's contribution to the paper	The candidate contributed 70% of the work for writing this paper. This work also received the 'Reviewer's favourite' award, which is only given to the papers with the top 10% reviewer's score, out of a total of 347 papers. She predominantly executed the following: <u>Formulation of ideas:</u> The candidate originated the idea for creating this collaborative work with the Grenoble Institute of Technology (GINP) in France. She also drove the vision of focusing on the replicability of hardware, after noticing a common thread in her research with that of the GINP. She also originated the idea of creating a flowchart showing the replication process of OSH. <u>Design of methodology:</u> The candidate designed the methodology in collaboration with the GINP colleagues and Dr Elies Dekoninck. She originated the idea which was used in the paper – to pool together our data for generating new insights on open source hardware replicability. <u>Experimental work:</u> The data used for this study are those from a survey carried out by the candidate, and those from interviews carried out by the authors from GINP. For the survey experimental work, please see the statement of authorship for the publication titled 'Defining Success in Open Source Hardware Development Projects: a Survey of Practitioners'. That survey data was analysed again by the researcher to specifically look at aspects of success related to hardware replicability. For the interviews, the authors from GINP revisited their data to focus specifically on hardware replicability. The findings from the two studies were then pooled together to develop rich insights.

	<u>Presentation of data in journal format:</u> The candidate wrote most of the manuscript (70%) and was the first author as well as the corresponding author. Professor Jean-Francois Boujut and Dr Romain Pinquié wrote the rest of the text. The researcher prepared the content of the flowchart showing the replication process of open source hardware, which was then finalised by Dr Amer Ezoji. Dr Elies Dekoninck supported the writing process by proofreading and giving ideas throughout.
Statement from Candidate	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.

Signed	Rafaella Antoniou	**Date**	18/08/2022

4.3 Paper B: Identifying the factors affecting the replicability of OSH projects

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4.3.1 Abstract[60]

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.

4.3.2 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 IP 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 (Bonvoisin, Mies, Boujut, et al. 2017; Bonvoisin et al. 2018; Balka 2011; Yanamandram and Panchal 2014b); business models (Pearce 2017); product development process organisation (Bonvoisin, Thomas, et al. 2017); community roles, behaviour and modes of participation (Li et al. 2019; Boujut 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

[60] A video abstract of the paper presented by the researcher can be viewed here: https://vimeo.com/594539300

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 not 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.

4.3.3 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 (Plesser 2018; National Academies of Sciences, Engineering 2019; Barba 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[61] 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

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

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.

4.3.3.1 Research aim

Nevertheless, with the recent development of OSH, the need for replicability was briefly discussed (Bonvoisin, Mies, Boujut, 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?

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.

4.3.4 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.

4.3.4.1 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.

4.3.4.2 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 19.

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 4.3.5.

4.3.5 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 19.

Table 19: 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	Farm Hack, Tympan, Echofab, Magnetic

Category	Factor	Description	Interviewed projects and survey responses
		that allows the rebuilding of the product.	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
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
Accessibility (continued)	Metadata and search	Metadata for facilitating the search and retrieval of existing designs, documentation and	Farm Hack, Echofab, Magnetic resonance

Category	Factor	Description	Interviewed projects and survey responses
		associated authors. How easy is it to find the documentation? How easy is it to view?	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.

4.3.6 OSH replicability process

The diagram in Figure 31 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).

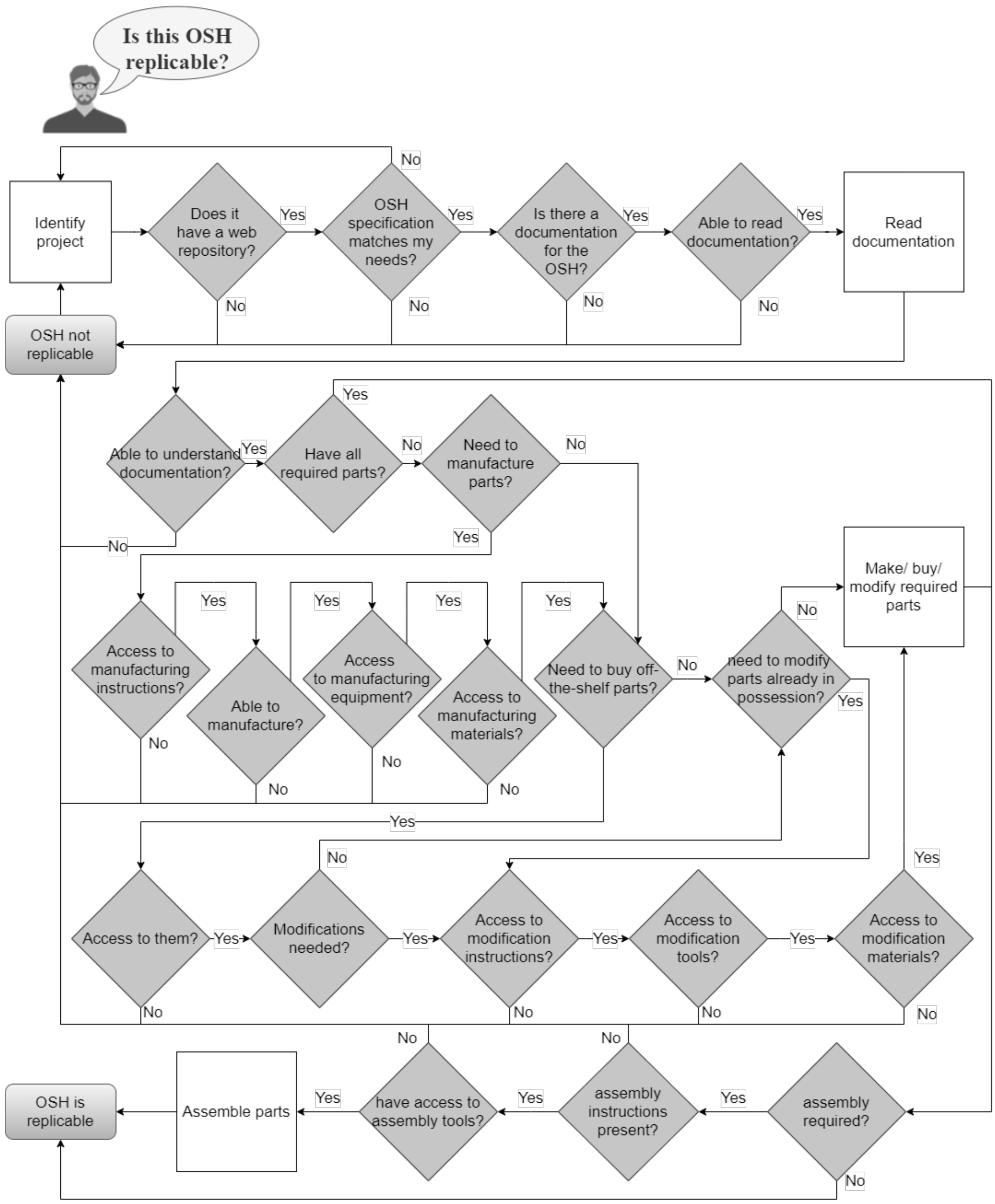

Figure 31: The process of determining whether an OSH is replicable.

4.3.7 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 20 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 20: 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	

Suggestion overview	Suggested practices	Replicability factors addressed
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	

4.3.8 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, Boujut, 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.

4.3.9 Acknowledgments

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4.4 Epilogue

This section further expands on the findings from study 2. Section 4.4.1 reflects on tacit knowledge as it relates to replicability in and section 4.4.2 discusses the applicability of replicability recommendations to the three project types identified in in study 2.

4.4.1 A reflection on tacit knowledge

Many of the factors affecting the replicability of OSH identified in paper B relate to documentation: its quality, completeness and accessibility. The endeavour of documentation is to effectively capture and transfer knowledge on how to build the hardware from the brains of its developer(s) to those of someone seeking to replicate it. That knowledge can be captured in the design itself, in the bill of materials, and other various documentation such as CAD drawings, assembly instructions, videos, images etc. As such, we can conclude that the replicability of a hardware heavily depends on effective knowledge capture and management.

However, a barrier to replicability always remains in the form of tacit i.e., implicit knowledge. Leonard and Sensiper (1998) pose that a lot of knowledge remains tacit for many reasons, such as (1) its codification does not appear to be beneficial (2) one is simply not aware of the tacit dimensions of their knowledge. For the former, incentivisation could help to overcome the perceived lack of benefit and for the latter, it is hard to say, and it is an interesting topic in knowledge research. It could also be hypothesised that effective documentation which helps achieve high replicability would depend upon effective capture of tacit knowledge.

4.4.2 Applicability of replicability recommendations to the three project types

Many of the recommendations presented in paper B require extensive documentation efforts by the project contributors. Dai et al. (2020) note that, in general, OSH participants are not motivated to document. They pose that this is because they are discouraged by the required time investment in combination with a lack of understanding of the value of knowledge codification. This is supported by Leonard and Sensiper (1998) as demonstrated in section 4.4.1. This lack of motivation to document may mean that many of the recommendations provided in Table 20 of paper B will not be implemented by OSH contributors. However, the fact that the recommended documentation practices given here are linked to increasing the replicability of OSH and, in that sense, the success of their project, might provide the motivation boost they need.

While replicability of hardware is a fundamental part of being open source – and so all projects will have it to a certain extent – the level of replicability may vary based on project characteristics. This is because different project characteristics may impose different constraints. For example, OSHD projects with an associated company may have business constraints on replicability that hobbyist projects may not have.

In this section, we investigate the suitability of using the typology presented in section 3 for developing best practice guidelines filtered by the OSHD project types. The three project types identified in section 3 were: hobbyist electronics; professional projects; and unfunded projects. Using the replicability guideline in paper B, we ask the question: can the typology be used to inform guidelines for specific project types?

4.4.2.1 Hobbyist electronics

Dai et al. (2020) noted a general lack of motivation to document amongst OSH contributors. In particular, one person they interviewed argued that participating in OSH projects is a hobby for them, and that participant expressed the sentiment "you do not document what you decide about your hobbies". If this sentiment is widespread amongst hobbyist OSH contributors, this may mean that the vast majority of the replicability recommendations that are proposed in paper B would not actually be feasible for hobbyist electronics projects. Indeed, the Hobbyist electronics project type was the only one in the typology study which did not have any projects containing contribution guides. This could be ascribed to the sentiment of not wanting to document about your hobby, but could also be explained with other reasons, e.g. the hobbyist project originators did not wish to collaborate with others on their personal projects.

The author hypothesises however that the suggestions under the overview "Use design for manufacturing and design for assembly good practice" in Table 20 would still be relevant for hobbyist OSH contributors. This is because educating hobbyist OSH contributors on the value of replicability considerations which could lead to project success could help motivate them to employ the recommended documentation practices. Furthermore, the author hypothesises that another factor contributing to the lack of motivation to document may also be the lack of education regarding good quality documentation practices. As such, a guideline such as the one in paper B could help address this. Future work could further investigate the sentiments of practitioners around documentation, barriers to documenting better and how to motivate practitioners to do so.

4.4.2.2 Professional projects

In section 3, we observed that professional projects are generally more often funded than other project types. In addition, they typically have a group of people working on the project. This means that they may have more resources, both financial and human, to apply towards implementing documentation guidelines. However, this would again depend on the motivation to document by the decision-makers in the project. It could be hypothesised that due to increased resources, there is a greater chance that these projects would document better. This provides an interesting avenue to explore in future studies.

They may also be interested in using design for manufacturing and design for assembly good practice, since this is generally good practice for product development and should help decrease the complexity of their product as well as the ease of manufacturing and assembly, potentially making it quicker and cheaper. For company-based projects with a business goal, profits are important and therefore keeping costs low would be important too. In this sense, it would be perhaps counterintuitive to funnel resources into better documentation, but that would depend on their motivation for openness and subsequently replicability. If project decision-makers deem that increasing replicability is a worthwhile investment of resources in terms of the value it will bring back to the project, the advice given in Table 20 would thus be very relevant.

4.4.2.3 Unfunded projects

By contrast to professional projects, unfunded projects do not have an as high level of financial resources to put towards better documentation. It could also be logically inferred that they also do not have many resources to put towards implementing design for manufacturing and design for assembly good practice unless that is already a modus operandi between the project participants, which often requires engineering design education. Another thing projects of this type have in common is that they have a diverse range of goals, which may mean there are different skill sets and different motivations involved. As such, replicability guidelines (and likely other types of guidelines, too) may have the most variability in their applicability. For example, engineering designers leading an unfunded project may have as a priority to produce the highest quality product, and therefore design for manufacture and assembly might be their top priority. Activists, on the other hand, may be more interested in making sure the OSH they develop is replicable in remote locations and, therefore, their priority might be to produce very high-quality documentation.

4.5 Conclusions

This section has shed light on an important aspect of openness: replicability. This has allowed investigation in more depth of the field of OSHD since openness is a key differentiating aspect of this type of product development. By analysing a key aspect of the field of OSHD, a further step is taken towards the characterisation of the field, the main aim of this thesis.

In Paper B, qualitative data were analysed to provide a detailed view of the factors affecting the replicability of OSH and through further analysis and logical reasoning those factors were used to provide suggestions for practitioners to improve the replicability of the OSH they develop.

Upon reflecting on Paper B, a short discussion on tacit knowledge was given. Further, the suggestions for increasing replicability in Paper B were discussed through the lens of the three project types identified in Section 3 (hobbyist electronics projects, professional projects and unfunded projects). At this point, it was concluded that while the advice given in the replicability guideline in Paper B can indeed be tailored to the project types identified in section 3, further work would be required to refine this filtering.

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Section 5. Conclusions and future work recommendations

This thesis presented three studies on OSHD: (1) one on project success through the perspective of OSHD practitioners (section 2) (2) one on creating a typology for OSHD projects based on their characteristics (section 3) and (3) one on understanding OSH replicability (section 4). Through the first two studies, we gained a broad understanding of OSHD by investigating project characteristics. For instance, in study 1 success was understood by identifying what characterises successful projects, while in study 2 several projects were categorised into types based on their similarities and differences. In the last study, the field of OSHD was studied by investigating the meaning of OSH replicability, and by extension, openness.

Section 5.1 reflects the research questions, research objectives and research aim laid out in Section 1. Section 5.2 presents in further detail the implications to knowledge generated by this thesis, providing a summary of key takeaways and outlining opportunities for future work. Lastly, this thesis concludes with a closing statement (section 5.3).

5.1 Reflection on research questions, research objectives and research aim

This section provides a reflective overview of the achievement of the research aim, research objectives and research questions set out in the introduction of this thesis (section 1).

5.1.1 Research questions

This thesis successfully addressed all the intended research questions and the outcomes of each are presented in Table 21.

Table 21: Thesis research questions with a summary of their outcomes.

Thesis section	**Informs research and/ or practice?**	**Research question(s)**	**Findings**
Section 2	Research, Practice	What characteristics and practices are present in successful OSHD projects?	Three top-level characteristics were identified. Successful OSHD projects: 1. Create value 2. Create high-quality outputs 3. Have effective processes. Multiple sub-characteristics (such as having replicable hardware, which links to the study in section 4) along with practices were identified for each of these top-level characteristics.

Thesis section	Informs research and/ or practice?	Research question(s)	Findings
		What metrics can be used to measure success in OSHD projects?	101 metrics were identified that are associated with each of the top-level characteristics.
		Does success look different in OSHD projects than in OSSD?	Success in OSHD and OSSD projects is mostly similar, based on a comparison with the literature. A few differences were identified and outlined, such as an OSSD study by Crowston et al. (2003) which found 'varied developers' to be a success measure while the study in section 2 found 'developers sharing similar expertise' instead.
		How does success in OSHD projects compare to success in NPD project management?	Only the cost and quality aspects of the iron triangle from NPD project management literature (completing a project on time, cost, and quality requirements) were confirmed in the study. Four out of the five dimensions of project success by Shenhar and Dvir (2007), namely: impact on the customer (the users), impact on the team (the contributors), business and direct success, and preparation for the future. The fifth dimension, efficiency, was not explicitly found in the study, but it could be linked to the third top-level success characteristic 'effective processes'. The study also compared the findings with the seven characteristics of highly successful projects by Dvir and Shenhar (2011), which were found to have limited applicability to the scope of the study.
Section 3	Research	What are the characteristics of OSHD projects?	A table of OSHD project characteristics was generated through expert interviews and a literature review (Table 13). Examples of the identified characteristics included product category, project goals and level of openness. Some of those were selected for the typology based on their relevance and feasibility of data collection.

Thesis section	Informs research and/ or practice?	Research question(s)	Findings
		What project 'types' can be identified based on the similarities and differences between the characteristics?	Three project types were identified through hierarchical cluster analysis using Ward's method and Squared Euclidean distance measure, with 9 clustering variables: 1. Hobbyist electronics projects 2. Professional projects 3. Unfunded projects
		What insights can be drawn from these project types?	Insights are discussed in terms of project goals, product domain, presence of a company, presence of funding, group versus solo contributions, presence of product sales, and project openness.
Section 4	Research, Practice	What are the factors affecting the replicability of OSH?	Assembly instructions and bill of materials are important, but they are not the only factors which influence how replicable an OSH is. The study identified a variety of factors and grouped them into four main categories: (1) quality, (2) completeness, (3) accessibility, and (4) ease of manufacture and assembly.
		What are the steps involved in replicating an OSH?	A flowchart of the replication process was created, which sheds light on the steps and decisions taken when an individual is attempting to replicate an OSH. It illustrates the different factors necessary to replicate an OSH.
		What project practices can be suggested for increasing the replicability of an OSH?	A table of suggested practices is given which addresses a variety of the identified replicability factors. Suggested practices include advice on creating good documentation, using design best practice and providing additional support to potential OSH builders.

5.1.2 Research objectives

In this section, the fulfilment of each research objective is discussed.

Objective 1: Understand how success is defined in OSHD projects and compare it to NPD and OSSD success.

Success in OSHD projects, from the perspective of practitioners, was investigated in study 1 in section 2. Some main themes were drawn as to which characteristics are present in successful projects, which can help with our understanding of OSHD projects as well as inform future studies. These characteristics were then compared to NPD and OSSD success literature, which further enhanced understanding of the similarities and differences across these fields. Overall, the above objective was met. Objective 1 could be further addressed in future studies by evaluating success in OSHD projects based on factors other than practitioner opinion.

Objective 2: Understand the breadth of variety of OSHD projects by identifying project types.

The breadth of variety of OSHD projects was explored in study 2 in section 3. Distinct project types were identified using a classification methodology of project characteristics which were distilled from the literature and expert interviews. Thus, Objective 2 is fulfilled. Objective 2 could continue to be addressed in future studies by obtaining data from a larger set of projects and/or more project characteristics.

Objective 3: Identify the factors affecting the replicability of OSH.

Objective 3 was addressed in study 3 in section 4 which identified the factors affecting the replicability of OSH. The above objective was fulfilled through the analysis of practitioner responses to a survey and interviews. This study went further than just identifying factors affecting replicability, and also made a first step in illustrating the replication process of an OSH as well as making recommendations on improving OSH replicability using the replication process diagram and the prior analysis. Objective 3 could continue to be investigated in future studies for example by carrying out controlled experiments in which people have to replicate an OSH based on the project's online information.

5.1.3 Research aim

The overall research aim of this thesis was to characterise the field of OSHD development. Overall, this aim was achieved through the three studies presented in sections 2-4. Each study in its own way contributed to the characterisation of the field. This is summarised in Table 22.

Table 22: A description of the contribution towards characterising the field of OSHD of each study presented in this thesis.

Thesis section	Study title	Contribution to characterisation of the field of OSHD
Section 2	Investigating the meaning of success in OSHD projects	Understanding how success is defined is an integral element for steering towards it. As a result, uncovering practitioners' thoughts on the topic is important for making a step towards identifying best practices. This can overall help to improve practice in the field. Additionally, project success in OSHD was compared to the literature on OSSD and NPD, which further helped with understanding the unique aspects of OSHD. Understanding project success also helps identify key factors in the field and identify areas for future research. All of these combined contribute towards the characterisation of the field of OSHD.
Section 3	A typology of OSHD projects	The development of a typology of OSHD projects helps characterise the field of OSHD because it contributes towards identifying project diversity, identifying patterns of characteristics between projects, and improving communication between practitioners by making a step towards providing a shared language for project types. The methodology of creating the typology also helps the characterisation of the field through the identification of salient project characteristics. In addition, this study has strong potential to be employed in the future at different points in time to compare the temporal variation across OSHD projects and project types.
Section 4	Understanding replicability in OSHD projects	Replicability is a core concept of openness, and as such, it is a core differentiating aspect of OSHD when compared with closed source NPD. Understanding replicability in OSHD projects can help identify barriers to replication and ways to improve it, thus informing development practices. In summary, understanding what factors influence it as well as ways to improve it helps identify the uniqueness of OSHD projects and characterise the field.

5.2 Implications and future work recommendations

In this section, the implications of each study in this thesis are summarised, along with some key future work recommendations.

5.2.1 OSHD project success

Study 1 presented in section 2 investigated the meaning of success in OSHD projects from the perspective of practitioners. The outcome was a variety of characteristics of successful projects aggregated at different levels. Figure 32 illustrates these characteristics in a mind map. The top-level characteristics of successful projects are that (1) they create value (2) they create high-quality outputs and (3) they have effective processes. Each of these top-level characteristics encapsulates other characteristics. For example, for the first one at the top 'successful projects create value' there are four medium-level characteristics: (a) projects create value to people and other projects, (b) they generate commercial value, (c) they create value sustainably and (d) they create value to the open source movement. The first of the medium-level characteristics 'successful projects create value to people and other projects' contained even more granular characteristics: (i) successful projects create value to contributors, (ii) successful projects provide value to users, (iii) successful projects create value to other projects, and (iv) successful projects create value to society.

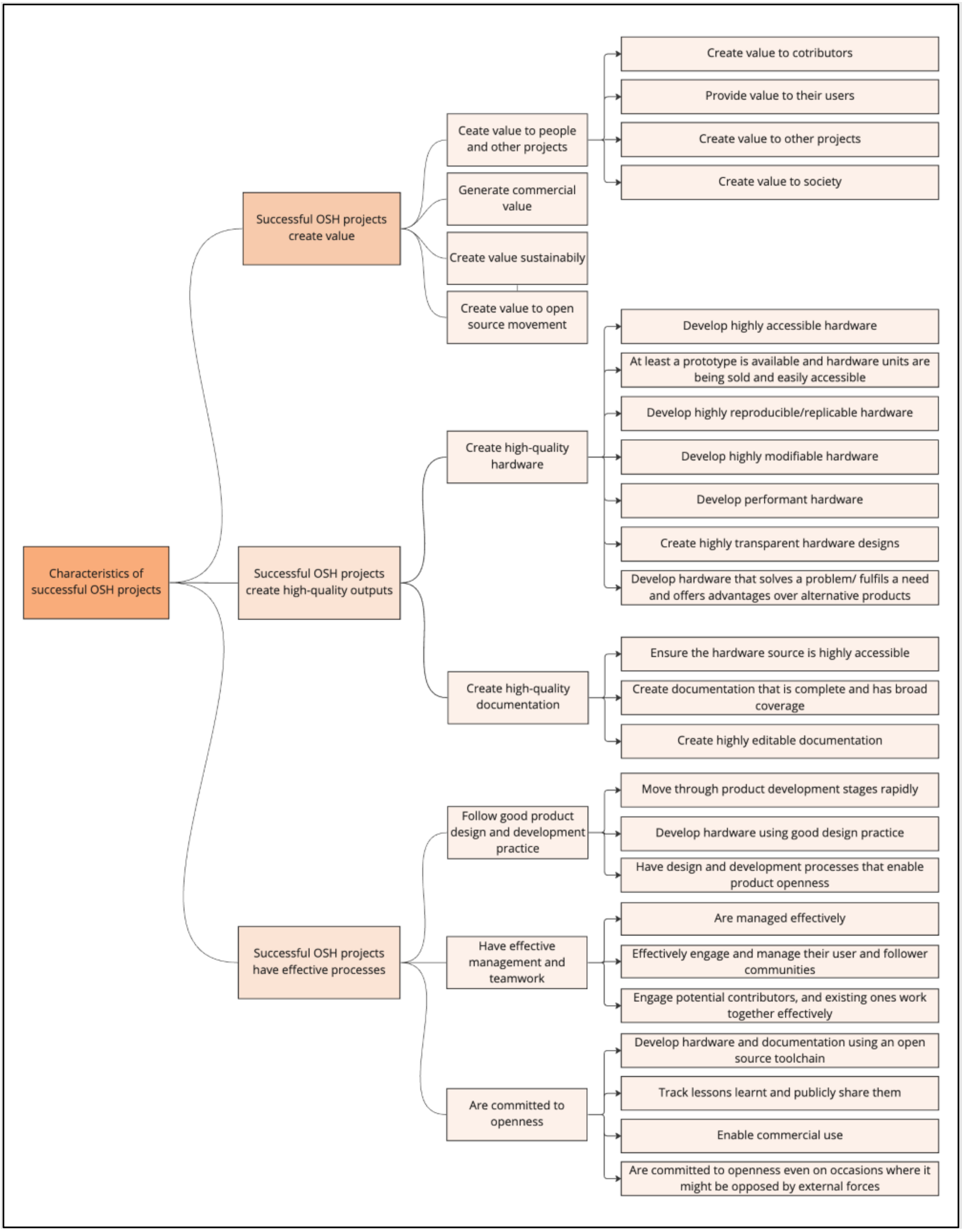

Figure 32: Summary of characteristics of successful OSHD projects generated from the analysis of a survey of practitioners, presented in section 2.

The first study in section 2 presented an understanding of success in OSHD projects through the eyes of practitioners. The study identified three themes in successful OSHD projects: value creation, quality of output and effective processes. Future studies could further investigate these themes with a larger sample size, as well as with purposeful sampling to collect the opinions of practitioners from a broad range of OSHD projects.

This would allow comparison with the findings of this study, as well as provide insights into any success characteristics that may have been missed. Additionally, future studies could collect data on projects at different points in time to observe temporal changes.

Additionally, this study presents a first step in looking at success in OSHD projects. A second step may be to create a framework for assessing success in OSHD projects. That may involve a study in which the importance of each characteristic of success is assessed for multiple projects. The most important characteristics could then be used to create a checklist, or alternatively, a weighting could be generated for each characteristic, for which the assessed project would be given a score. The total score a project would get would therefore indicate how successful it was.

It could be concluded that project success characteristics will not be one-size-fits-all for OSHD projects. As such, another avenue for research would be investigating the applicability of the project success characteristics across different kinds of projects. Another way of approaching a success assessment framework may be to include a pre-assessment step where a project representative first assesses the importance of each project characteristic for their specific project. This could be used to generate a weighting for each characteristic. Then, the projects can be scored on the different characteristics. The score could then be multiplied by the weighting to obtain a weighted score, and then all the scores added to obtain a total. Such a project success assessment can aid comparison between projects and could help researchers investigate project success and failure. For example, case studies could be done on low-scoring projects to assess why they 'failed' and on high-scoring projects to assess why they 'succeeded'. Such case studies and comparisons could help provide insights into potential reasons why projects succeed or fail (theoretical contribution) and could help contribute towards developing best practice guidelines (practical contribution).

Further studies into success in OSHD projects could also include quantitative studies investigating the probability of project success based on different project characteristics, such as goals. Such studies could help shed light on the relationships between certain variables and project success. Moreover, future studies could look into the relationships between different characteristics and how those impact success. For example, case studies could study projects with different goals and assess their success using a framework. Lastly, an interesting avenue of research could be investigating project failure, and such the factors which can possibly lead to project success or failure.

5.2.2 Typology of OSHD projects

The second study involved creating a typology of OSHD projects. The main takeaways from this study are:

1. A list of variables which characterise OSHD projects (Table 13) generated through a literature review and expert interviews.

2. A methodological framework for data collection for some of those variables for different projects.
3. A methodological framework for creating a typology of those projects based on the collected variables.
4. An initial typology of OSHD projects consisting of three types: hobbyist electronics projects, professional projects and unfunded projects.

The typology study in Section 3 presented a methodology for determining types of OSHD projects. 16 binary variables were used for data collection, of which 9 were selected for the analysis through a systematic process of elimination of highly correlated variables and swamping variables. A number of additional variables characterising OSHD projects were identified through a literature review but were not used in the study due to methodological reasons for data collection. Further studies could employ different data collection methods, such as interviews with participants, to collect data on those variables and observe whether the types emerging are different.

Another interesting avenue for future work is to employ this methodology at different points in time and observe whether the dominant types of OSHD projects change or not. This would provide a temporal view of the landscape of the OSHD field. Additionally, the methodology could be employed at different points in time for a dataset of specific projects. This could provide insights as to whether projects evolve into different types.

In section 4, the outcomes of the typology from section 3 were used to discuss the suitability of suggestions for practitioners for increasing the replicability of the OSH they develop according to the different project types. Future studies could employ the typology for informing a variety of different best practice advice and assess its helpfulness in doing so. For instance, projects belonging to different project types could be investigated through case studies to generate a more detailed understanding of the applicability of best practice advice to each project. The generalisability of that advice to the entire project type could be explored by conducting a large number of case studies and, if possible, large-N studies.

5.2.3 OSH replicability

The third study presented in section 4 involved investigating a core element of openness in OSH – replicability. It challenges the assumption made by some authors (e.g., Bonvoisin et al. (2017)) that OSH replicability is only determined by the presence of assembly instructions and a bill of materials by uncovering an array of factors influencing the replicability of OSH generated through analysing questionnaire and interview qualitative data. It also explored the replication process and applies the knowledge of the factors affecting replicability by providing suggested practices for practitioners for improving the replicability of an OSH. Furthermore, it offers a discussion of the applicability of those suggested practices to the three project types identified in section 3.

Future research could build on the findings of this study by creating tests for replicating an OSH and evaluating whether the suggested practices given in Section 4 improve the replicability. To do this, however, replicability metrics would need to be generated first, which would then be measured before and after the suggested practice intervention. In addition, individuals would have to be recruited to participate in the replication, and skill levels would have to be considered. Another key element of consideration in such a study would be hardware complexity. If a hardware is highly complex, then it follows that it would be more difficult to replicate. However, there are practices that a project can consider which would improve the replicability despite the complexity, and therefore such future studies would have to consider how to take into account hardware complexity when testing replicability.

Additional future work could also focus on other aspects of openness beyond replicability – such as transparency and accessibility (Balka et al. 2014) and any others – and their relationships amongst each other. This would allow for a greater, more holistic understanding of openness within the context of OSH and as such, would allow for greater characterisation of the field through the understanding of this fundamental unique aspect.

5.3 Closing statement

In summary, this thesis provides a characterisation of the field of OSHD projects, including an exploration into the meaning of success in OSHD projects through the point of view of practitioners, the identification of key characteristics which differentiate OSHD projects, as well as the creation of a typology for categorising OSHD projects. It highlights the uniqueness and nuance of the field.

Additionally, the thesis contributes to the deeper understanding of the field of OSHD by examining a core concept of openness – replicability – including the factors that influence it and some recommendations for practitioners for improving it in their projects. Moreover, a discussion on the applicability of the typology for informing practical interventions for replicability is given. Through these contributions, this thesis advances the maturity of the field of OSHD and provides valuable insights for research and practical applications. As this new phenomenon evolves, the research approaches given in this thesis could be implemented again to assess the evolution of the field.

During the process of developing this research, the researcher gained expertise and experience in the field by presenting in conferences, publishing in a peer-reviewed conference and journal (receiving citations from some of the most prominent researchers in the field of OSHD) and working in an EU-funded research project focusing on OSHD in which she participated in the writing of a book on OSHD.

All in all, this thesis represents an important step in our understanding of the new phenomenon of OSHD. It is also timely and relevant, since this field is growing and receiving significant research attention, and it is hoped that this work will serve as a foundation for further research.

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