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Publication status and date:

Published: 20/04/2023

Document Version

Publisher's PDF, also known as Version of record

Citation for the published version (APA):

Carpentier, P. (2023). *A new frontier for the study of the commons: Open-source hardware*. [Doctoral Thesis, Erasmus University Rotterdam].

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Rotterdam School of Management
Erasmus University

Pascal Carpentier

A New Frontier for the Study of the Commons

Open-Source Hardware



**A New Frontier for the Study of the Commons:
Open-source hardware**

**A New Frontier for the Study of the Commons:
Open-source hardware**

Een nieuwe wereld voor de studie van de commons:
Open-source hardware

Thesis

to obtain the degree of Doctor from the
Erasmus University Rotterdam
by command of the
rector magnificus

Prof. dr. A.L. Bredenoord

and in accordance with the decision of the Doctorate Board.

The public defence shall be held on
Thursday 20 April 2023 at 15:30hrs

by

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Erasmus Research Institute of Management – ERIM

The joint research institute of the Rotterdam School of Management (RSM)
and the Erasmus School of Economics (ESE) at the Erasmus University Rotterdam
Internet: www.irim.eur.nl

ERIM Electronic Series Portal: www.pure.eur.nl

ERIM PT PhD Series in Research in Management, 10

ISBN 978-90-5892-656-2

© 2022, Pascal Carpentier

Design: PanArt, www.panart.nl

Print: OBT bv, www.obt.eu

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This publication (cover and interior) is printed on FSC® paper Magno Satin MC.



Acknowledgments

A Ph.D. is a journey more than a destination; beyond this manuscript, the main outcome of this endeavor has been my evolution as an individual on a personal journey, with many enriching encounters over the past five years. Here, I would like to acknowledge and thank all the individuals who helped me to grow and, I hope, become a better version of myself.

I would like to begin by acknowledging my professors, Prof. Dr. Lucas Meijs and Prof. Dr. Ir. Vareska van de Vrande, who guided me throughout this thesis. You have my greatest gratitude.

I also would like to thank my life partner, Armelle, for her ongoing support; she has had to put up with me all these years and cope with my absences. A word of gratitude also to my daughters, who let me study quietly while they wanted to play with their dad.

This journey would have been impossible without the formidable support of my employer, the non-profit drug research and development organization Drugs for Neglected Diseases initiative (DNDi), which created the conditions that allowed me to achieve an unreasonable amount of work in parallel with a full-time job. Thanks to Thomas Saugnac, who made this personal project a reality, and Dr. Louise Burrows, who was instrumental in editing and improving my articles.

I would also like to thank all the individuals involved in communities who dedicated time to a wannabe researcher: Dave and Sophie from Lowimpact—what you do for the planet is great!; Mathilde, Mehdi, Olivier, and others at the echOpen community; Lionel at Ideavox; Fabio, crusader of open models in global health; and Dr. Pierre Longchamp for your time and expertise in medical devices.

Thank you also to the legal innovation researchers from Neuchatel University, Prof. Dr. Daniel Kraus and Quentin Adler, who are relentlessly trying to innovate in the

legal field to support open movements. Your work is very inspiring and particularly needed by commons communities.

Thank you, Dr. Simon Grant from the P2P foundation, for challenging my work, and Prof. Dr. Benjamin Coriat for convincing my employer that commons are a key success factor for its mission.

I cannot thank everyone I met during this journey, but I wanted to mention two very welcoming researcher communities: the Open User Innovation (OUI) and the International Association for the study of the commons (IASC). It wasn't an easy task to put myself in the shoes of a researcher, and these two communities created the conditions for me to transition smoothly and in an empowered way. Very open to multidisciplinary approaches, they allowed me to find my unique way of contributing to the debate.

To all of you, I express these words of appreciation.

Pascal Carpentier
Geneva, December 2022

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List of abbreviations

CBPP	Commons-Based Peer Production
CEI	Commons of Entrepreneurial Innovation
CMTIR	Commons of Material and Technological Innovation Inputs and Resources
CPR	Common-Pool Resources
EMA	European Medicines Agency
FLOSS	Free/Libre and Open Source Software
FDA	Food and Drug Administration
GAFAM	Google, Apple, Facebook, Amazon, Microsoft
GDPR	General Data Protection Regulation
GKCF	Governing Knowledge Commons Framework
HC	Hybridized Commons
IC	Innovation Commons
KC	Knowledge Commons
LMIC	Low and Middle-Income Country
NFP	Not-For-Profit
OSH	Open Source Hardware
OSPD	Open Source Product Development
OSS	Open Source Software
OSSD	Open Source Software Development
OUI	Open User Innovation
SDT	Self Determination Theory
SEM	Structural Equation Modeling
TC	Traditional Commons
WKC	Web-based Knowledge Community

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1. Introduction

The great virtue of the commons framework is its ability to make sense of new phenomena.

Bollier and Helfrich (2014, p. 347)

1.1 Thesis themes and relevance

Commons have existed since antiquity, structuring and ruling the management of shared resources. Their first historical trace can be found around 1370 BC when Pharaoh Akhenaten established a nature reserve in Egypt (Bollier & Helfrich, 2014, p. 347). Although challenging to characterize, commons can be considered as “holistic social institutions to govern the (re)production of resources, articulated through interrelated legal, socio-cultural, economic and institutional dimensions” (Dulong de Rosnay & Stalder, 2020). This definition not only highlights the various dimensions to consider when studying these social institutions, but also unveils the institutional flexibility that is core to commons’ strength. Thus, in recent decades, scholars have increasingly studied commons as they have proved to be efficient in addressing various complex contemporary shared-resource management issues (Laerhoven et al., 2020). Historically, commons have been designed to address natural resource consumption and preservation issues such as grazing, water, forests, or fisheries management (Cox et al., 2010; Gibson et al., 2000; Ostrom, 1990). Nowadays, they support very different types of resources at various scales from Global Commons (Scott et al., 2022; Vogler, 2012) with a planetary scope dealing with climate change (Ansari et al., 2013), to more localized ones, like Urban Commons (Łapniewska, 2016).

Furthermore, commons are relevant for an ever-increasing range of resources. As technological progress pushes the limit of what can be subject to social dilemmas, what was once non-rival becomes rival: “commons emerge as the technology

evolves, technology enables to capture what was previously uncapturable” (Hess, 2008). Therefore, new resources have become subject to potential tragedies where “freedom in a commons brings ruin to all” (Hardin, 1968); for instance, outer space polluted by debris (Wang, 2013), the electromagnetic spectrum subject to congestion (Soroos, 1982), or DNA studies that are far too complex for a single entity to decipher (Cook-Deegan & McGuire, 2017).

In the 1990s, scholars started to consider how common-pool resources (CPR) could be “ideas” or information instead of “things”; for example, genetic information (Contreras, 2014), airplane innovations (Meyer, 2014), the blockchain network (Murtazashvili et al., 2022), or software engineering (Schweik & English, 2012). Commons dealing with intangible resources are more complex to manage since they have to deal with the production of resources in addition to their consumption and protection (Madison et al. 2010; Cole 2014). In addition to the historical role of protecting resources, this new generation of commons has become a means of production, opening a third way between “market and states” to produce products and services in a non-commoditized way. Over the past few decades, knowledge and digital commons have proved to be complete game-changers in innovation and collaboration. Their virtual nature allows vast communities freed from the limitations of the tangible world to gather, coordinate, and collectively produce goods (Benkler & Nissenbaum, 2006) and services (Rheingold, 2003). This has allowed an unprecedented production of knowledge, accelerated by the intensification of the exchange of information among people and communities; a phenomenon sometimes referred to as “the cornucopia of the commons” (Rose, 1986).

A novel socioeconomic model of production has emerged, with many people working together toward the same collective goal without financial compensation. This has opened a non-commoditized way of producing goods (Benkler, 2006); a successful example would be the Open Source Software (OSS) movement, which

has even become a mainstream way of producing operating systems for mobile phones or servers.

Over the past fifteen years, technological evolution has allowed hobbyists and amateurs to exchange information and techniques to build tangible objects and not just computer programs (Cohendet et al., 2021; Hansen & Howard, 2013). This has opened a new field of open source development, Open Source Hardware (OSH), which aims to replicate the OSS model's success but in the physical world with tangible resources (Raasch et al., 2009; Schweisfurth et al., 2011). The complexity of OSH products has drastically increased from simple objects printed in 3D to more ambitious or even complex projects like an Open MRI (Winter et al., 2019). Some projects have become real commercial successes, like Arduino, which has sold more than 10 million units¹ of its multipurpose electronic board. OSH communities' ethos is to make hardware design available to anyone to contribute, improve, and distribute a piece of equipment; they actively promote this mode of production not only to accelerate innovation and reduce R&D costs (Pandey & Vora, 2019; Pearce, 2015b; Williams et al., 2012), but also to lower repair costs and improve product quality (Gibb & Abadie, 2014; Gibney, 2016). However, the comparative advantage of the proprietary model is not yet fully understood (Huang, 2015) and, globally, there is a dearth of research in the literature given how young this development model is (Pandey & Vora, 2019).

The COVID pandemic recently acted as a catalyst for OSH projects, which were suddenly under the spotlight worldwide. Communities helped healthcare workers to face the sanitary crisis with countless medical spare parts, respirators, or face shields² (Maia Chagas et al., 2020). Although this commons-based mode of production (Benkler & Nissenbaum, 2006) demonstrated a genuine capacity to propose pragmatic and decentralized solutions to this unprecedented situation of

¹ [10M Arduino Uno boards sold worldwide \(controldesign.com\)](https://www.controldesign.com/10m-arduino-uno-boards-sold-worldwide/)

² [COVID-19 Ventilators \(pubinv.org\)](https://pubinv.org/covid-19-ventilators/)

generalized supply chain disruption, the vast majority of these projects failed to reach the hospital bedside. These communities underestimated the gap between being willing to share knowledge, building functioning prototypes, and getting a final product up and running in a hospital (Cennamo et al., 2022). Therefore, we aim to describe how commons can bring actionable solutions to support this new open source movement and deliver complex OSH projects. It is worth noting that this thesis focuses on complex OSH projects since many OSH projects are data-centric and implemented merely by a few execution steps at the end of data manipulation (Troxler, 2010). For instance, 3D printing is not very different from a classical OSS project with the majority of work performed in the digital realm. Thus, we focus on complex projects, often in the medical field, combining diverse expertise and large-scale collaboration between individuals and public or private organizations. This allows us to observe significant differences with well-known commons described in the literature.

Academically speaking, OSH communities are fascinating objects of study that push the limits conceptualized in classical commons theories. They use and produce tangible and intangible shared resources, solve associated social dilemmas, and overcome combined constraints. These communities blur the well-defined lines separating Traditional Commons (TC), usually dealing with consumption of tangible resources, and Knowledge Commons (KC), supporting the enrichment of intangible shared resources. This heterogeneity in the nature of shared resources introduces extra complexity to realizing these projects. The emerging literature on what is sometimes called Hybridized Commons (HC) indicates that a new generation of commons supports these communities. Moreover, an increasing number of application fields, such as agricultural innovation and innovation management (Basu et al., 2017; Potts, 2019), already rely on this new type of commons.

Thus, in this thesis, we explore the specificities and challenges these communities face that commons can help to solve, and how they facilitate project delivery of

innovative products in the real world. This is in a field considered the new frontier for the study of the commons (Bollier & Helfrich, 2014, p. 177), or the next digital revolution (Gershenfeld, 2005; Troxler, 2010): Open Source Hardware.

1.2 Objectives and research questions

At the core of this thesis, we explore commons supporting complex OSH projects, the governance of which tends to be more complex than purely digital commons or TC. OSH communities are KCs that have to deal with the material scarcity of hardware equipment (Filippi & Troxler, 2016) and cope with limited community size due to physical constraints (Bonvoisin et al., 2018; Boujut et al., 2019). In addition, they retain the complexity of KCs and have to organize the production of their shared resources, both tangible and intangible. Moreover, the OSH ecosystem is still in an early phase of its development after a decade of expansion; scholars are still struggling to address various challenges hindering OSH communities' ability to deliver end products. For instance, it is still unclear how to build a successful business model for OSH initiatives (Li & Seering, 2019; Pearce, 2017). There is also a lack of dedicated development tools and software platforms to support this movement (Hansen & Howard, 2013). Legal protection strategies are numerous and complex for non-professionals to implement (Marrali, 2014). Finally, the products developed by these communities may be subject to industry regulations requiring extra development constraints and specific expertise (Bergsland et al., 2014). In this context, commons bring flexible institutional arrangements that have proved instrumental in various community-powered projects and have helped to realize countless project objectives (Laerhoven & Barnes, 2014; Schweik & English, 2012). Among other benefits, commons open doors to highly specialized expertise without being cash-intensive (Potts, 2019). They also protect the software development that often supports the hardware core of the project. Therefore, we anticipate that commons may play a significant role in helping the OSH movement to thrive and deliver complex projects in an immature environment. Thus, we propose the following global research question (RQ): *How can commons support OSH movements and foster complex project delivery?*

Madison et al. (2019) described commons as governance regimes based on various institutional arrangements coordinating the interaction between a community and shared resources with formal or informal rules, laws, social norms, or technology. Therefore, to answer our global RQ, in the following chapters, we will approach commons from three angles of study. First, in Chapter 3, as governance regimes for resources created and owned collectively (Dedeurwaerdere et al., 2014). Second, in Chapter 4, as groups of individuals sharing an objective, norms, and social practices to manage the access, usage, and (re)production of shared resources (Coriat, 2015). Finally, Chapter 5 will study the shared-resource angle as described by Charlotte Hess (2012): “a commons is a resource shared by a group of people that is subject to social dilemmas.” Thus, we have articulated the following RQs to improve our understanding of commons’ contribution to complex project delivery:

- i. Commons operate in a conceptual *terra nullius* between state and market (Caffentzis, 2008), with a continuous struggle to be recognized by the state (Hess, 2008). This is particularly true for industry regulation and the state delegating power to an agency. In Chapter 3, we focus on commons governance evolution to answer RQ1: *How can Knowledge Commons adapt to industry regulations and place a product on the market?*
- ii. A discussion on commons is incomplete without dealing with communities (Fournier, 2013; Laerhoven & Barnes, 2014). This dimension is often overlooked, and communities’ various internal relations are neglected. We will pay particular attention to these communities’ evolution, transformation, and motivation. In Chapter 4, we will focus quantitatively on community motivation to address RQ2: *Do individual motivations influence knowledge sharing differently for two groups observed within web-based knowledge communities?*

- iii. In literature, natural and knowledge commons are treated separately. However, products can combine natural and knowledge resources; for instance, rice crop production (Basu et al., 2017) or Innovation Commons (Allen & Potts, 2016; Potts, 2019). Commons can pool relevant information and tangible resources to achieve innovations. In Chapter 5, we investigate how the shared resource at the core of the commons can change along a product development pipeline. Hence, RQ3: *How do commons evolve to support the development of innovative projects?*

Commons are constantly evolving living social systems (Bollier & Helfrich, 2019). Therefore, in the following chapters, we provide a temporal perspective to account for this evolution (Wittel, 2013), answering the call from Madison et al. (2017) to study KC governance over the long term. Moreover, in Chapter 5 we dedicate a complete longitudinal study to the same community to accurately capture a decade of evolution. Finally, although commons are usually studied by qualitative methods, Chapter 4 describes a quantitative study of a very mature and stable digital community, giving us precious insight into critical motivators for enduring KCs. This thesis relies on various research methodologies, with two qualitative studies and one quantitative. First, we conduct an exploratory case study focused on the influence of industry regulation on OSH. We rely on the governing knowledge common framework (GKCF) from Frischmann et al. (2014) to structure our approach and untangle the interactions between resources, participants, and governance structures. In Chapter 4, we adopt a quantitative approach with data collected via a digital survey. Our analysis uses structural equation modeling (SEM), a statistical technique for testing relationships between constructs with multiple measurement items (Joreskog & Sorbom, 1996). Finally, Chapter 5 features a longitudinal case study using a process research methodology (Van de Ven & Huber, 1990; Van de Ven & Poole, 2002).

This manuscript aims to contribute to various literature strains, on commons, OSH, and, more globally, on open source. In particular, we propose future research paths at the crossroads of commons and OSH. Thus, in the following chapters, we explore commons in OSH, enriching these two nascent research fields (Chapters 3 & 5). We also advance the recent literature on Innovation Commons (IC) by providing one of the first case studies on this new form of commons (Chapter 5). Chapter 4 deals with communities' motivations and refines our understanding of community members' long-term involvement in commons. Finally, we shed light on why industry regulation has increasingly become a challenge to commons, and how this should be addressed (Chapters 3 & 5).

We also intend to propose managerial recommendations to increase the success rate of OSH projects and improve their ability to deliver a functional product or service. Thus, we investigate how commons could be leveraged to deliver complex collective projects or initiatives. While, sometimes, participating in a commons – that is, commoning – can be seen as an end in itself (Linebaugh, 2008), the social practice may prevail over delivering the community's project. This often results in the delivery of mere prototypes, technical toolboxes, or proofs of concept usable for further development. In contrast, in this manuscript, we focus on commons as means to deliver a fully functional and usable end product. We aim to understand how commons could become a robust alternative means of production in the OSH field and help deliver a final product to the same standards as a commoditized product.

1.3 Outline of the dissertation

This thesis is structured as follows: an introduction, a literature review, three empirical chapters, and a general reflection and discussion.

The three empirical chapters have been published or submitted to peer-reviewed journals. Hence, the reader may experience overlaps in the narrative of these chapters. With this dissertation, our ambition is to bring an overarching view to the study of the commons and propose new research paths on recently identified forms of commons.

In **Chapter 2**, we introduce the theoretical foundations relevant to this thesis, understanding and positioning this work in the vast field of commons studies.

First, we will describe how the nature of a shared resource can lead to self-organization to manage resource sustainability, hence creating a commons. To better understand what commons really are, we will go back to their origin to study when the rival nature of a shared resource made its management a source of tension. Then, we will describe how the intangible nature of a new kind of shared resource gave birth to a new member of the commons family: the KC. We will focus on the specificities of the governance of KCs: managing access to the resource and the production of it.

Finally, we will introduce the last aspect of a commons: the community. We will discuss how commons create communities and how communities gather to create commons to manage shared resources.

Chapter 3 is an exploratory case study focusing on the influence of industry regulation on an OSH project. In this case, the shared resource is subject to medical industry regulation, resulting in unexpected constraints on the project's supporting commons and substantial governance modifications.

RQ1: How can Knowledge Commons adapt to industry regulations and place a product on the market?

Abstract: Tools for clinical examination have not fundamentally evolved since the invention of the stethoscope by René Laennec in the nineteenth century. However, three decades ago, the medical community started to consider repurposing ultrasound scanners to improve physical examinations. A broad community of healthcare professionals trained in the new clinical examination paradigm could not be created due to the very high price of portable ultrasound scanners available on the market. In this paper, we study an OSH community that aims to improve diagnosis in hospitals and medically underserved areas worldwide. The community is designing an echo-stethoscope (a portable ultrasound scanner) that would be affordable in low and middle-income countries (LMICs). The variety of expertise pooled to achieve this objective puts this knowledge common (KC) at the crossroads of OSS, OSH, and medical communities. Unlike typical KC outcomes, an ultrasound probe is a physical object. Development and innovation in the physical world bring social dilemmas that the community has to overcome, restrictions in terms of openness, and, in this case, unintended privatization. Our study uses the GKCF, a modified institutional analysis and development framework, to untangle the interactions between resources, participants, and governance structures.

Our research describes why and how the creation of a physical object subject to industry regulation influences the evolution and governance of the KC. We provide evidence that temporary privatization of the KC can be used as a way to protect and sustain a commons during the industrialization phase. We also demonstrate how a portfolio of projects is an effective and resilient way to help the common survive this privatization step.

This chapter has been published: Carpentier, P. (2021). Open Source Hardware, Exploring how Industry Regulation Affects Knowledge

Chapter 4 challenges the idea that communities are homogeneous and their members are equally motivated to participate in knowledge-sharing activities. In this quantitative study, we collected data via an electronic survey sent to over 9,000 individuals. We relied on SEM to obtain insights on long-term participation in a KC.

RQ2: Do individual motivations influence knowledge sharing differently for the two groups observed within web-based knowledge communities?

Abstract: Over the last three decades, the Internet has allowed people to connect, communicate, and share information on topics of interest. Websites and wiki-like sites have become the new libraries, active agoras for seeking and sharing information and knowledge. At the heart of this thriving knowledge, commons comprise individuals who invest time and energy to create content and make it available online.

Intrigued by this behavior, scholars have extensively studied what motivates web-based knowledge community (WKC) members to share their knowledge. However, the results of these studies often consider community members as a homogeneous population, particularly when it comes to understanding their motivations. Furthermore, emerging literature provides evidence within these communities of an uneven distribution of the workload involved in creating valuable content. A minority of the members create the vast majority of content, another small proportion edits and comments on existing content, while most members solely read the available content. Understanding what motivates the minority of individuals who make a large contribution is crucial to the survival and growth of these communities.

In this paper, we survey a WKC sharing experience on sustainable living and ecology. This community is composed of topic experts and registered site members,

and we questioned them on their motivations for participating in and contributing to the community. We relied on self-determination theory (SDT) to introduce a novel construct to assess how their sense of identification with the community goal affects their knowledge-sharing behavior. This construct turned out to have a very significant effect on community members' motivation.

Moreover, our results reveal fundamental differences between participants' motivations for sharing knowledge within a WKC, depending on their contribution level. Thanks to our refined understanding of these differences, we can formulate more granular recommendations to web community managers and website administrators, allowing more targeted actions to increase participation and involvement.

This chapter has been published: Carpentier, P. (2021). Understanding individual motivations among members of online communities. *Les Cahiers du numérique*, 17, 153-183. DOI: <https://doi.org/10.3166/LCN.2021.006>

Chapter 5 is a longitudinal case study on an OSH community covering almost ten years of collective history. We relied on a process methodology to articulate how the very nature of the shared resource within the commons can change during project development.

RQ3: How do commons evolve to support the development of innovative projects?

Abstract: Innovation is often considered the holy grail of modern organizations. For a long time, innovation has been considered the result of genius or visionary's epiphany. Research and empirical evidence have proved this assumption wrong. Modern theories suggest that innovations are often the result of circumstances that bring together knowledge previously dispersed among many actors. Thus, scholars recommend embracing knowledge sharing and open processes to foster innovation. In this context, communities have become increasingly prominent and have been shown to be game-changers in software and, more recently, hardware development.

These communities thrive when supported by digital or KC, bringing a flexible form of governance to develop and protect their collective work.

This paper focuses on an emerging form of commons: the IC. These commons are temporary and appear at the early stage of an innovation trajectory. They help to pool latent expertise that was initially distributed among various individuals. Hence, they contribute to assessing the feasibility of a project and to reducing any uncertainty about its execution.

In this article, we conduct an in-depth longitudinal case study of an OSH community developing a disruptive medical device. Several types of commons supported this innovative project during nine years of product development. We propose a process theory to explain the temporal order and sequence in which these commons formed and disappeared. We uncover the underlying mechanisms explaining why these supporting commons evolve and why they evolve as they do.

Our paper also contributes to the nascent literature on IC. Our case study confirms existing theories on IC structure and further describes the disappearance of the IC during project development.

Finally, we provide empirical evidence that by creating the conditions needed to professionalize the community and its original legal structures gradually, IC was essential to the successful outcome of this decade-long collective project.

Chapter 6 is our general conclusion. First, we review every chapter's findings; we then discuss how our work helps us to better understand the role commons can play as agile and dynamic institutional arrangements in the OSH field. We end the thesis by providing an overarching conclusion, implications for practice, and avenues for future research.

1.4 Declaration of contribution

I single-authored all the chapters of this dissertation. However, I would like to thank and acknowledge all the individuals who spent their precious time reading, commenting, and improving the quality of this work.

Chapter 1: I worked independently to complete this chapter under the supervision of Prof. Dr. L. C. P. M. Meijs and Prof. Dr. Vareska van de Vrande. They provided valuable suggestions and comments, which I incorporated.

Chapter 2: I worked independently to complete this chapter under the supervision of Prof. Dr. L. C. P. M. Meijs and Prof. Dr. Vareska van de Vrande. They provided valuable suggestions and comments, which I incorporated.

Chapter 3: A draft of this article was sent to my supervisors, Prof. Dr. L. C. P. M. Meijs and Prof. Dr. Vareska van de Vrande, for comments; I incorporated their feedback. I would also like to thank Dr. Louise Burrows for her help with editing the manuscript and Dr. Pierre Longchamp for his review of the regulatory sections of this paper. Finally, I received valuable feedback from anonymous reviewers that drastically improved the quality of the article, which was published with the following reference:

Carpentier, P. (2021). Open Source Hardware, Exploring How Industry Regulation Affects Knowledge Commons Governance: An Exploratory Case Study. *International Journal of the Commons*, 15(1), 154–169. DOI: <https://doi.org/10.5334/ijc.1081>

Chapter 4: A draft of this article was sent to my supervisors, Prof. Dr. L. C. P. M. Meijs and Prof. Dr. Vareska van de Vrande, for comments; I incorporated their feedback. I would like to thank Dr. Louise Burrows for her help with editing the manuscript. Finally, I received valuable feedback from anonymous reviewers that drastically improved the quality of the article, which was published with the following reference:

Carpentier, P. (2021). Understanding Individual Motivations among Members of Online Communities. *Les Cahiers du numérique*, 17, 153–183.

DOI: <https://doi.org/10.3166/LCN.2021.006>

Chapter 5: A draft of this article was sent to my supervisors, Prof. Dr. L. C. P. M. Meijs and Prof. Dr. Vareska van de Vrande, for comments; I incorporated their feedback. I would like to thank Dr. Louise Burrows for her help with editing the manuscript. This article has been submitted to a peer-reviewed journal and is currently under review.

Chapter 6 (Conclusion): I worked independently to complete this chapter under the supervision of Prof. Dr. L. C. P. M. Meijs and Prof. Dr. Vareska van de Vrande. They both provided valuable suggestions and comments, which I incorporated.

2. Introduction to the commons

This chapter covers theoretical foundations that could not be included in the following chapters due to word limitations for publication. We will articulate our introduction to the commons around our three main angles of study; the governance regime, the resource management, and the communities powering commons. Furthermore, we will instill a chronological perspective highlighting the successive waves of commons creation following technological innovations and their impact on the above. This combined approach helps us to articulate how a variety of commons supports OSH projects and comprises solutions to specific challenges this emerging type of community is facing.

2.1 Traditional commons: A story of shared resources

The law locks up the man or woman, who steals the goose from off
the common
But leaves the greater villain loose, who steals the common from off
the goose.
(eighteenth-century protest song)

Commons have existed for centuries in various countries to address traditional or rural communal life resource management issues (Ostrom, 1990). They can be defined as “social systems in which resources are shared by a community of users/producers, who also define the modes of use and production, distribution and circulation of these resources through democratic and horizontal forms of governance” (Angelis & Harvie, 2014). This decentralized self-governance regime was common in Europe during the medieval period (Castro, 2021) until an enclosure movement started in England during the thirteenth century, which turned these communal lands into private property to increase land productivity (Zückert, 2012). The enclosure movement revoked farmers’ right to access these communal lands

and was stimulated by a significant increase of the value of these lands for a minority of wealthy individuals (Linebaugh, 2008). Commons became rare and almost disappeared for centuries (Dulong de Rosnay & Stalder, 2020). Hence, the study of this governance regime was overlooked until the twentieth century.

According to Hardin (1968), the world is led by self-interest, where individuals are solely motivated by maximizing their benefit in a resource-constrained setting. This behavior produces an inevitable resource depletion called the tragedy of the commons. Hardin posited that only private property or a solid external authority (e.g., a state) could solve this dilemma, and proposed two alternatives:

i) A market-based solution that would privatize the resource and divide it between various stakeholders. ii) An external regulator that would enforce communal rules at a sustainable level for the resource.

This view has dominated policymakers' debates on commons' management for over half a century.

Hardin had a pessimistic view of humanity, which depicted an unmanaged commons with an open access resource without rules to manage and share the resource adequately. However, commons do not offer open access to shared resources. Quite the contrary: People communicate and self-organize to protect and sustain their shared resource. Ultimately, the publication of Hardin's article acted as a wake-up call to the study of the commons, leading to a Nobel prize being awarded to Elinor Ostrom in 2009.

2.1.1 Introducing subtractability and excludability

Elinor Ostrom elaborated Samuelson's (1954) classic distinction between collective goods and private goods. She enriched the model by adding the CPR characterized by the combination of high subtractability and high difficulty to exclude a potential beneficiary (Table 2-1).

i) *Subtractability* or rivalry are constructs that measure how a resource is impacted when used or consumed. In such cases, two things can happen: Either the resource will be gone until it is replaced (e.g., grass for grazing), or it will remain available for further use (e.g., a journal article). If someone reads a journal article, this will not prevent someone else from reading the same article afterward.

ii) *Excludability* describes whether it is possible to prevent access to a resource. For instance, one could build a wall to protect private property, but preventing individuals from pumping water out of a river is nearly impossible.

		Subtractability of use	
		High <i>rivalrous</i> goods	Low <i>non-rivalrous</i> goods
Difficulty of excluding potential beneficiaries	High	Common-pool resources (common goods): groundwater, fisheries, forests etc.	Public goods: peace and security
	Low	Private goods: food, clothing, etc.	Toll goods (club goods): Private clubs, theatre

Table 2-1: Type of good. Adapted from Ostrom (2009)

High subtractability and low excludability create tension and dilemmas for shared-resource users. There are plenty of cases with natural resources; for instance with forests (Gibson et al., 2000) or fisheries (Acheson, 1988). Commons are self-governed regimes established to manage and solve these dilemmas. This classification of goods also applies to intangible assets like knowledge or digital assets (Schweik & English, 2012) that could artificially be made excludable (Boyle, 2008). Moreover, a type of good can change over time: Resources can see their excludability and rivalry evolve, or an intangible private good can become a public good (De Moor, 2012). For instance, a journal article could be under embargo before publication with high excludability before becoming open access. This is one of the

complexities of commons: The type of a good is not solely related to its intrinsic nature but can also be the result of a governance decision (Coriat, 2011). Hence, in this manuscript, we will mainly allude to the notion of shared resources to depict goods without making assumptions about their subtractability and excludability.

2.1.2 A space of formal or informal governance

For the magnitude of the sea is such, as to be sufficient for the use of all nations, to allow them without inconvenience and prejudice to each other the right of fishing, sailing, or any other advantage which that element affords.

Hugo Grotius (1625)

Hardin (1994) acknowledged that his tragedy of the commons resulted from an “unmanaged commons” situation. He described open access to shared resources without any form of governance, such as rules or constraints. Thus, what he was describing was actually the tragedy of an unmanaged commons.

In a commons, commoners decide to establish “rules in use,” a set of formal or informal governance rules to address social dilemmas that could arise regarding the shared resource, typically problems of access, maintenance, or over-consumption. Someone who does not respect the rules of use is called a free-rider, and could be an individual or a group of individuals who take advantage of a shared resource. If this behavior becomes prevalent, it could lead to the destruction of the resource. Hence, sustainable commons require the establishment of suitable rules respected by all users of the shared resource. To this end, appropriate governance plays a crucial role in ensuring the long-term sustainability and proper functioning of the commons to “achieve compatibility between interests of the different actors, working on the assumption that these interests do not necessarily coincide” (Ostrom, 1990).

According to Ostrom (1990), research about commons should be empirical rather than conceptual (Frischmann, 2013). Thus, there is no clear definition of what rules must be implemented for a sustainable commons. Instead, Ostrom proposed eight design principles that can be found in robust, enduring common-pool resource institutions. These principles highlight the importance of self-managed, self-governed structures. Additionally, they represent a complete disruption of the traditional method of tackling social dilemmas raised by the exploitation of natural shared resources.

- i. Define clear group boundaries regarding who has access to what to avoid free-riding.
- ii. Match commons governance rules to local needs and conditions. There is no one-size-fits-all approach; instead, rules are established by the local population to fit that specific environment.
- iii. Ensure that community members affected by the rules can participate in modifying the rules.
- iv. Outside authorities must respect the rule-making rights of community members.
- v. Community members develop their own monitoring systems, so communities ensure that people follow the established rules.
- vi. Use graduated sanctions for rule violators.
- vii. Provide low-cost and accessible means for dispute resolution.
- viii. Build responsibility for governing the common resource from the lowest level up to the entire system.

Since the inception of these empirical design principles in 1990, their validity has been confirmed (Cox et al., 2010), shaping the contour of long-lasting commons' governance. Moreover, beyond these design principles, commons governance offers the flexibility to attribute different rights to community members. According to Coriat (2011), a commons is “a set of resources that are collectively managed by

means of a structure of governance that distribute rights between the commoners and aims to ensure the well-ordered, sustainable exploitation of the resource.” He introduces how commons are self-governed by a formal or informal regime that allocates a *bundle of rights* to various groups of stakeholders (Schlager & Ostrom, 1992).

2.1.3 Common property and bundles of rights

The originality of the commons’ governance is the uncoupling of resource ownership and distributed rights to use or manage it (Table 2-2). An ad hoc series of rights can be established according to the nature of the resource and its property regime. These rights among commoners may be guaranteed by either the law or local customs and may evolve but are subject to discussion within the commons. Most importantly, these rights and obligations must be respected, otherwise commoners are subject to penalties. Table 2-2 shows distributed rights between the partners involved in the exploitation of a resource in a commons:

- i. Access and withdrawal: The right to access and withdraw part of the resource. “Authorized users” are allowed to access and withdraw a resource by others that hold the collective management rights.
- ii. Management: The right to improve a resource and regulate its internal use (i.e., how, when, and where harvesting could occur). “Claimants,” in addition to the authorized users’ rights, can participate in the collective management of rights at an operational level.
- iii. Exclusion: A collective right to decide who has access and how this right can be transferred. “Proprietors” have, on top of claimants’ rights, authority over who may access the resource and how it may be utilized. They do not have the right to alienate either of these collective-choice rights.
- iv. Alienation: A collective right facilitating the transfer of all the abovementioned rights to another individual or group, which typically involves selling or leasing these rights. This right is exercised by “Owners.”

		Owner	Proprietor	Claimant	Authorized user
Access	and	X	X	X	X
withdrawal					
Management		X	X	X	
Exclusion		X	X		
Alienation		X			

Table 2-2: Bundles of rights associated with positions(Schlager & Ostrom, 1992)

Commons can be relevant solutions to bring together stakeholders with sometimes diverging interests in producing or exploiting a shared resource (Ostrom, 1990). It is achieved through a subtle and unique balance of rules in use and a bundle of rights constantly adapted by community members or the resource owner. The idea of a bundle of rights became a source of inspiration for designing governance rules of the Free/Libre and Open Source Software community (Markus, 2007). Thus, the following section describes how commons are meaningful institutional governance mechanisms for intangible resources such as knowledge or digital assets.

2.2 Introducing Knowledge Commons

First, it is essential to define the notion of knowledge. In this thesis, we consider knowledge as all forms of information, data, and ideas at any stage of the wisdom hierarchy (Davenport & Prusak, 1998; Henry, 1974). Moreover, we complement this list with cultural resources, including books, paintings, music, and other products of the mind (Boyle, 2008; Ostrom & Hess, 2007).

2.2.1 Intangible shared resource

During the 1990s, new type of commons began to flourish:

It was around that time [1995] that we began to see a new usage of the concept of the “commons.” There appears to have been a spontaneous explosion of “ah ha” moments when multiple users on the Internet one day sat up, probably in frustration, and said, “Hey! This is a shared resource!” People started to notice behaviors and conditions on the web—congestion, free-riding, conflict, overuse, and “pollution”—that had long been identified with other types of commons. They began to notice that this new conduit of distributing information was neither a private nor strictly a public resource.

(Ostrom & Hess, 2007)

Wikipedia is one of the most prominent KCs available to date (Kittur et al., 2007), but it is far from being the only successful example. According to Dedeurwaerdere et al. (2014), KCs represent effective institutionalized community governance in various fields such as software (Schweik & English, 2012), microprocessor development (Legenvre et al., 2020), medical information commons (Bubela et al., 2019), microbial commons (Dedeurwaerdere, 2010), radio spectra (Wormbs, 2011; Heinrich-Francke, 2011), public libraries (Nwagwu & Matobako, 2021), and even

the Galaxy classification with the Galaxy Zoo project, where nonscientists helped classify galaxies in a giant online database (Madison, 2014). In the medical field of rare or neglected diseases, KCs support initiatives to invent new medicines that are not profitable enough for pharmaceutical companies (Abecassis et al., 2019; Strandburg et al., 2014). They are widely used in various industries since they allow information sharing while respecting intellectual property and copyrights (Sanfilippo et al., 2019). Some outstanding projects have indicated that KCs and network-based developments may be efficient strategies for achieving superior innovation for a lower cost than closed innovation models while protecting intellectual property (Abecassis et al., 2019; Hall, 2010).

As described in Table 2-3, a KC's *raison d'être* is to enrich and maintain a shared resource; thus, they constitute a compelling mode of production of information and knowledge. For instance, the scientific community is accustomed to *stand[ing] on the shoulders of giants* to solve complex problems that no person or organization could solve alone. Furthermore, KCs have virtually no limit to the number of participants in the commons and have changed significantly the way knowledge is produced and circulated while protecting and guaranteeing innovators' intellectual property and copyrights (Allen & Potts, 2015, 2016; Potts, 2017). Moreover, in software development, OSS has become a mainstream and cost-effective way to develop novel technology (Carillo & Okoli, 2008; Pearce, 2017). For instance, as of July 2019, 86% of smartphones relied on Linux as their operating system³. Moreover, various open initiatives have delivered artifacts capable of becoming leaders in some high-tech sectors; they have demonstrated that highly specialized skills and expertise could be managed effectively within commons (Schweik & English, 2012).

³ <https://www.idc.com/promo/smartphone-market-share/os>

	Traditional Commons	Knowledge Commons
Nature of shared resource	Rival	Non-rival
Property regime/Governance	Users are authorized to use the resource to secure its future	Each user is encouraged to contribute and grow the resource
Community	Reproduction of the shared resource	Enrichment and growth of the shared resource

Table 2-3: Differences between traditional commons and knowledge commons - adapted from Coriat (2011)

2.2.1.1 Intangible but subject to tragedies

In the mid-1990s, the emergence of the Internet and the generalization of digital resources facilitated the duplication and distribution of texts, images, videos, and audio documents with nearly nonexistent marginal costs. Scholars began to consider information as a commons and the Internet as a free resource subject to social dilemmas such as network congestion and free-riding (Gupta et al., 1997; Huberman & Lukose, 1997). Additionally, scholars realized that knowledge and digital assets available via the Internet were subject to typical commons challenges (pollution, enclosure, free-riding, privatization, scarcity, and degradation). Ultimately, Digital Commons had their own tragedy, sometimes called the tragedy of the Digital Commons (Adar & Huberman, 2000; Greco & Floridi, 2004). For instance, communities supporting OSS development are subject to this tragedy when there is a lack of incentive to contribute to the commons (Schweik & English, 2007). Anyone with an internet connection can freely download and use OSS regardless of their level of community participation. Hence, it is crucial for communities to motivate individuals to join them and support their effort above and beyond the audience that is genuinely interested in the usage of the software.

Next, Chapter 4 provides further insights into this phenomenon through a quantitative study of why people participate and share knowledge in web-based KCs.

Digital information exchange via the Internet has created conditions producing an abundance of KCs and alternative models of knowledge production, such as commons-based peer production (CBPP) (Benkler 2006; Benkler and Nissenbaum 2006). However, this unprecedented exchange of information has faced an unexpected threat. Private actors began legal actions and claimed property rights over previously shared resources, what Boyle called “the enclosure of the intangible commons of the mind” (Boyle, 2003). Subsequently, this enclosure movement boosted the structuration of various open movements in many digital fields (Boyle, 1997; Lessig, 2001).

2.2.1.2 Second enclosure movement

The general rule of law is that:

[T]he noblest of human productions—knowledge, truths ascertained, conceptions, and ideas—become, after voluntary communication to others, free as the air to common use.

Supreme Court Justice Brandeis (1918)

For the past century, intellectual property rights have been considered the exception rather than the norm. Ideas and knowledge, in general, have been considered a public good. In the 1980s, however, a series of intellectual property rights laws and court rulings created the conditions for the appropriation and enclosure of what was historically open access (Coriat & Orsi, 2002). The legislator’s initial intent was to incentivize innovation by securing companies’ returns on investment. This policy change had an overwhelming impact; the number of patents in many fields increased (e.g., human genome, genetically modified organisms, algorithms, information technology, pharmaceuticals, living organisms). Over time, this capacity to block

others from using a patent idea or concept eventually became an obstacle to many innovators and communities, eventually constituting the tragedy of the anticommons (Heller & Eisenberg, 1998).

Although this enclosure movement could mean the end for the KC, it instead acted as a catalyst and led to an increased number of creations (Hess & Ostrom, 2003). These commons thrived as an alternative to the enclosure movement (Aigrain, 2005); communities gathered and established KCs to produce or protect their digital assets (Bollier, 2008; Dedeurwaerdere et al., 2014; Laerhoven & Ostrom, 2007). The generalization of the Internet not only lowered transaction and replication costs but also provided nearly universal access to information and strongly contributed to this expansion (Benkler, 2004). Along with this digital revolution, new methods of production were developed, such as common-based peer production (Benkler, 2006) and private-collective models of innovation, in which individuals and companies co-design innovations (Hippel & Krogh, 2003). In Chapters 3 and 5 these decentralized models to produce and innovate will be discussed in depth.

2.2.2 Protecting Knowledge Commons

As with any other commons, social dilemmas can appear, requiring a specific set of formal or informal governance mechanisms. However, compared to TC (Table 2-3), KC communities must organize their shared-resource production before agreeing on how to share it (Burke & Kraut, 2008). Therefore, these communities tend to develop formal or informal policies or procedures to improve their production quality or fight against their virtual resource pollution. For instance, Stack Exchange, a highly specialized technical online forum, structures with internal procedures how community members should answer questions on its forum (Matthews, 2016) and the Wikipedia community self-organizes to fight against disinformation (Saez-Trumper, 2019). Additionally, these guidelines can be

established as an answer to formal legal constraints (Dulong de Rosnay & Stalder, 2020).

Once the production of the shared resource is governed, commoners must agree upon a way to share and protect the fruit of their collective work. An appropriate level of intellectual property protection helps a commons grow and thrive. For instance, authors and innovators who choose to make their work available for free can still retain their copyrights and grant the right to others to continue their work under certain conditions, thanks to an instrumental legal innovation that took birth in the software field.

In the early 1980s, an MIT engineer named Richard Stallman became frustrated with a software license that prevented him from improving software that was inadequate for his needs. In effect, since the 1970s, software had been patentable and subject to copyright, which prevented Stallman from modifying the code of the software he was using. Thus, together with the lawyer Eben Moglen, they developed the concept of “copyleft” to counter copyright, a legal mechanism that automatically protects original works of authorship. Additionally, this team developed the General Public License (GPL); the first copyleft license promoting the following four fundamental freedoms related to programming and coding (Stallman, 1996):

- i. the freedom to run software for any purpose,
- ii. the freedom to study and change a program without restrictions,
- iii. the freedom to distribute copies of a program, and
- iv. the freedom to distribute changes of a program.

To summarize, copyleft is an authorization given by an author of a creation of the mind (e.g., art, text, code) to use, study, modify, and broadcast their work, assuming this authorization is transmitted along with the good it regulates. Thus, someone modifying an artifact subject to a copyleft license must, in turn, redistribute their work under the same conditions as the original. The license is inherited, and the same conditions of use apply recursively, so this type of license is often called a

viral license. Overall, this legal innovation has increased knowledge sharing and fostered the creation of new content while respecting copyright laws. Stallman described this copyleft mechanism in an interview with Byte magazine in 1986⁴: “[I] see [copyleft] as a form of intellectual jujitsu, using the legal system that software hoarders have set up against them.” For instance, copyleft has been successfully implemented by the creative commons association, which proposes a wide variety of standardized licenses to encourage sharing while respecting intellectual property. A well-known example would be Wikipedia articles that are under a creative commons ShareAlike license: CC-BY-SA. In this case, CC-BY means it is allowed to share, edit, and develop the original article for any purpose, even commercially, if authors are appropriately credited. SA stands for ShareAlike and means that the modified material must be distributed under the same license.

Creative Commons can be applied to far more than text, images, and software code; they are for instance used in drug discovery. The Open Source Malaria project⁵ proposes an open license to encourage the scientific community to find new drugs and treat malaria: “The default license for everything in the Open Source Malaria project is CC-BY, meaning you can use whatever you want for any reason (including to make money) provided you cite the project.” These examples are not exhaustive but show that intellectual property is a central concern when working within a KC or in crowdsourced project developments (Beer et al., 2017). Occasionally, the intellectual property itself is the reason for creating a commons to resist enclosure and commoditization (Broca & Coriat, 2015).

⁴ David Betz and Jon Edwards, “Richard Stallman discusses his public-domain [sic] Unix-compatible software system with BYTE editors,” BYTE (July, 1996). (Reprinted on the GNU Project web site: <http://www.gnu.org/gnu/byte-interview.html>.)

⁵ <http://opensourcemalaria.org/>

2.2.3 Protecting Open Source Hardware

OSH communities are recent members of the KC family, albeit the protection of these commons is similar to the protection of OSS commons but not as straightforward. These communities produce tangible objects, but the protection mechanisms described above rely on copyright, which automatically protects authors of products of the mind. However, this mechanism does not apply to ideas or objects; copyright protects only the schematics and documentation of these objects, which can easily be circumvented by minor technical modifications (Ackermann, 2009). Therefore, the absence of a copyright's comprehensive and automatic protection is a major challenge hindering OSH communities' ability to become world-class actors (Marrali, 2014). In the past, OSH communities thrived in the absence of an existing market for their product. However, they are at risk in more competitive environments without suitable protection, and defenseless in front of an enclosure or free-riding attempts. Patents could be a suitable solution to protect the work produced by these communities, but this mechanism is an antagonist to most OSH communities' ethos. The second enclosure movement and its negative effects on innovation made it a last resort option for these communities gathered by the idea to build and share openly (Bergsland et al., 2014; Chien, 2013). Alternatives, such as defensive patenting or releasing all technical sources to the public domain, could be considered to prevent others from patenting one's innovation against one's community (Beldiman & Fluechter, 2018; Schultz & Urban, 2012). These considerations are subject to intense discussion within communities since this topic is highly controversial. Unusually, disagreements on this issue could lead to a collective decision to fork the project, meaning part of a community leaves with a copy of the technical sources to create an alternative project and community (Außendorf, 2015; Nyman & Mikkonen, 2011). In the following chapters, we propose research paths to improve OSH community work protection and help them to scale up sustainably.

Next, the final section of the introductory chapter explores communities and social practices powering commons.

2.3 Once upon a community

[T]he commons imply a plurality of people (a community) sharing resources and governing them and their own relations and (re)production processes through horizontal doing in common, commoning.

De Angelis (2017, p. 10)

Commons are often solely considered a convenient tool to manage scarce resources, but they are also the fruit of a collective story involving individuals creating or joining communities to achieve something collectively. Charlotte Hess (2008) highlighted various reasons for people to gather and create commons, including a sense of sharing, joint ownership, and a need to protect a shared resource from enclosure, privatization, or commodification.

In the collective unconscious, innovations are technological breakthroughs embodied by a highly gifted individual working alone, usually referred to as a genius (Woodmansee, 1984). Although this mythical image is widespread, significant achievements are rarely the fruit of a single gifted individual. Scholars used to say that they stand on the shoulders of giants to acknowledge that their work is the fruit of their predecessors as well. A famous quote later twisted into “We stand on the shoulders of ordinary people, not only on the shoulders of giants” during the Open and User Innovation conference 2021 by Professor Carlisse Baldwin. She stressed that anyone could participate in producing innovations, knowledge, and even products or services (Benkler, 2006). Commoners are conscious that communities are melting pots where “individual contributions and collective effort enablement” are blended and tend to be proselytes of this collective way of creation (Stalder, 2018).

Unlike Hardin’s prediction, there is a consensus among scholars and practitioners that communities can be very effective governing bodies (Berge & Laerhoven,

2011; Laerhoven & Barnes, 2014; Ostrom, 1990). With Hardin, people were considered the source of the tragedy of the commons. However, since Ostrom, they are considered a critical part of the solution when they self-organize within communities (Agrawal & Gibson, 1999).

2.3.1 From communities to virtual communities

Commons and communities are two similar notions that sometimes overlap or are used interchangeably. However, although all commons have at least a community, not all communities are commons. Thus, “No commons without a community” is an accepted statement in the study of commons (Caffentzis & Federici, 2014; Mies, 2014). In this manuscript, we will always allude to communities that are part of commons and therefore use the terms “commons” and “community” interchangeably.

First, communities are composed of members with similar interests who share a common culture or discourse (Berkes et al., 1989; Coe & Bunnell, 2003; Mies, 2014). Their formal or informal organization is dynamic, horizontal, and nonhierarchical (Richardson, 2015). They are often defined geographically as places or territories and include homogeneous social norms (Agrawal & Gibson, 1999; Wellman & Gulia, 2018). Additionally, geography limits communities’ size, especially for TCs. If a community contains more than a few hundred actors, Ostrom argued that it would require a nested decision-making structure because direct contact between all participants would become extremely difficult.

In early 2000, the digital revolution represented a formidable opportunity for commoners to share information and connect with people moved by similar ambitions all over the world. Thus, these communities became global, containing virtually unlimited participants (Coriat, 2011). They benefited from new digital platforms to communicate and simplify their governance (Dietz et al., 2003; Frischmann et al., 2014).

Some of these virtual communities produced significant innovations in knowledge-intensive areas, even competing with proprietary innovations. The objective of these communities also vary greatly, from mitigating the negative ecological impact of human activities as described in Chapter 4, to simply developing something helpful or fighting the commodification movement. Frequently, these peer production communities aim to produce something useful, unlike traditional market actors that aim to develop products to sell. Benkler (2002a) described these communities as “groups of individuals [who] successfully collaborate on large-scale projects following a diverse cluster of motivational drives and social signals, rather than market prices or managerial commands.” Community members invest their time and energy because they enjoy these activities and share a common objective of wanting to give back to their community (Chou, 2010; Nov, 2007; Wasko & Faraj, 2005). For instance, DCs are a successful example of countering legal enclosure in the digital realm and as models of equitable knowledge dissemination (Dulong de Rosnay & Stalder, 2020). These virtual communities proved that this collective production mode is a credible alternative to a centralized mode of production. In particular, they can deliver digital products and adequately manage internal production processes without a legal entity. Furthermore, legal status plays a nearly negligible role in a classical institutional analysis applied to commons (Dulong de Rosnay & Le Crosnier, 2012).

However, many mature communities have decided to create a foundation to undertake financial, legal, and regulatory work that a group of volunteers could not perform alone. Currently, large communities in OSS or OSH frequently set up foundations (Dulong de Rosnay & Stalder, 2020). Thus, Chapters 3 and 5 expose serious dilemmas caused by this transition from unstructured communities to a formal legal entity.

2.3.2 Challenges of commoning

Commons are living social systems through which people address their shared problems in self-organized ways.

Bollier and Helfrich (2019)

Some scholars consider societal and social arrangements involving shared resources within a community to be commons. In such cases, these commons are conceptualized as social productions resulting from human–human and human–nature interactions with a collective objective (Basu, 2016; Öztürk et al., 2014). Thus, these commons result from a social process and a governance regime. In some cases, the product and its production process become inseparable, particularly with intangible shared resources (Basu, 2016; Hardt & Negri, 2009). Other scholars have described commons as noncommodified ways of fulfilling social needs to obtain social wealth and organize social production (Angelis & Harvie, 2014). Commoners benefit from participating in this collective process; they learn new things, feel good about their achievements, and boost their self-esteem. Chapter 4 analyzes psychological mechanisms motivating one to participate actively in knowledge-sharing activities.

In sum, commons are broader than problem-solving and purpose-oriented entities; they also encompass social relations and practices that produce or reproduce commons. This practice, called “commoning,” extends the notion of commons beyond its governance regimes and rules to embrace commoners’ social practices (Akbulut, 2017). However, this social practice brings both additional norms and further constraints. For instance, an overly strong top-down hierarchy could be perceived as threatening freedom and cause “reactance,” a psychological defense reaction to regain lost freedom (Brehm, 1966). Conversely, too little structure could increase conflict and thus defection.

In virtual communities dealing with intangible shared resources, one must consider members' motivations to contribute to growing the resource, that is, knowledge creation. If too many active members quit a commons, that commons may end. Moreover, in KCs, active community members usually represent a small portion of the people involved in the overall community (Bonvoisin et al., 2018; Xu et al., 2009). Additionally, most OSH and OSS projects do not attract many contributors, so they never really thrive, instead remaining inactive or dormant (Özkil, 2017). Therefore, governing a community is a subtle exercise for the sake of the shared resource and for the benefit of members who will be more inclined to participate actively.

Finally, a community does not exist in a void; it is subject to interactions with the outside world, state actors, donors, or NGOs. Consequently, informal governance and the absence of a legal entity can impede community survival or growth in the long run. Likewise, applicable laws and industry regulations can lead a community to its end in certain circumstances (Laerhoven & Barnes, 2014).

In particular, OSH initiatives face many new challenges that commons could help overcome. Nevertheless, these emerging constraints also influence the commons' governance and may have fatal consequences if not anticipated. In the following chapters, we will explore this bidirectional relationship, how commons support innovative OSH projects, and how these projects affect commons governance and evolution.

In the next chapter, we will first explore the implications of industry regulations on commons governance.

3. Open Source Hardware, exploring how industry regulation affects knowledge commons governance: An exploratory case study⁶

3.1 Introduction

Innovations in the medical field have been instrumental in improving public health and quality of life (WHO, 2010). Medical technologies (Medtech) help to prevent diseases, diagnose, and treat patients. However, Medtech innovations have not always been widely available and accessible to LMICs. Fragmented regulation (Bergsland et al., 2014; De Maria et al., 2018), high prices, and inadequate solutions for local markets (Malkin & von Oldenburg Beer, 2013) are the typical barriers hindering product adoption. According to the World Health Organization (WHO), in the cardiac disease field alone, more than 2 million patients die worldwide every year due to lack of access to an implantable cardiac defibrillator or pacemaker (Ochasi & Clark, 2015).

Access and distribution are two fundamental principles of the open source movement. Initiated in the mid-1980s, this movement paved the way for an open and collaborative approach to developing software. Groups of independent developers sharing similar interests gathered (Benkler, 2002b, 2006; Benkler & Nissenbaum, 2006) to create OSS communities. Today this practice has become a dominant way of producing critical software, such as operating systems for telephones and servers (Pearce, 2017).

⁶ This chapter has been published under the following reference. Carpentier, P. (2021). Open Source Hardware, Exploring How Industry Regulation Affects Knowledge Commons Governance: An Exploratory Case Study. *International Journal of the Commons*, 15(1), 154–169. DOI: <https://doi.org/10.5334/ijc.1081>

With the emergence of 3D printing and fab labs, open source communities started to build tangible objects and made their designs freely available over the internet (Gibb & Abadie, 2014; Raasch et al., 2009). This extension from purely digital to physical product development gave birth to a new form of product development and distribution, OSH, which “is hardware whose source files are publicly available for anyone to use, remanufacture, redesign and resell” (Gibb & Abadie, 2014, p. xiii). OSH recently demonstrated its relevance in the medical field as an alternative way to provide technical solutions in the case of pandemics disrupting supply chains. It allowed decentralized production of respirators, visors, and spare parts as a rapid response to emergency needs (Maia Chagas et al., 2020). Furthermore, making hardware design available under an open source license allows anyone to contribute and improve the device, thus accelerating innovation at a fraction of the cost (Pandey & Vora, 2019; Pearce, 2015b; Williams et al., 2012).

Open source initiatives can be seen as community-powered projects that are often managed informally and aim to create and share a common knowledge (Coriat, 2011). They constitute a Knowledge Common (KC), a self-governed form of community created to produce and manage a particular type of resource: knowledge (Ostrom & Hess, 2007).

At first sight, OSH communities are very similar to OSS communities and other KCs. However, due to the extra constraints resulting from their interaction with the tangible world, they differ in many aspects (Ackermann, 2009; Beldiman & Fluechter, 2018). This case study is set in the medical industry, an environment that is highly regulated to ensure patient safety. OSH Communities developing medical devices have to comply with stringent quality controls and audits (Abuhav, 2018), but this regulation has been designed for commercial enterprises and is inadequate for non-profit organizations or for informal institutional arrangements. As a result, these communities' efforts are frustrated and generate various social dilemmas the community has to overcome to achieve their goals.

Regulation has a substantial impact on these KCs governance and product development (Powell, 2012). With this case study, we intend to understand how KCs can adapt to industry regulations and ultimately place a product on the market. We followed echOpen, a community started in 2014, involving people interested in m-health and e-health devices worldwide. The project involves physicians who have fostered and developed the concept of echo-stethoscopy – the use of ultra-portable ultrasound imaging devices to enhance diagnosis during a clinical examination – for 30 years (Elezi, 2018). Their ambition is to build an affordable ultrasound probe and make it available to hospitals and medically underserved areas worldwide. They initiated a KC composed of more than 500 healthcare professionals, scholars, students, and engineers. We relied on the GKCF (Frischmann et al., 2014) to understand the evolution of this KC, a modified version of Elinor Ostrom and Charlotte Hess' institutional analysis and development framework adapted to knowledge as a resource. We gained insights into product development up to the industrialization stage, a stage that has potentially fatal implications for OSH projects and their community of volunteers in a regulated industry.

A legal entity must be accountable for manufacturing a device before it is allowed on the market for use on patients. In this case study, there was unintended privatization of the Common that was at odds with the commoners' expectations and which could have led to the end of the common. This study sheds light on mechanisms helping KCs survive regulation-driven privatization which goes against the open source community's ethos. Moreover, through the lens of KCs, we provide guidance to anticipate and cope with the extra complexity OSH projects entail.

This paper describes the Open source movement's theoretical foundations, including both the well-established OSS and emerging OSH branches. We describe why open source models are an effective way to innovate in the medical device industry and pay particular attention to the regulatory framework of medical devices. It also

introduces institutional arrangements used to produce and manage information or digital assets: the KC.

An exploratory case study is then presented following the GKCF approach, which describes how various stakeholders interact and govern the common to produce knowledge and overcome social dilemmas.

The final section elaborates on the findings, discusses limitations and potential ways forward for further research.

3.2 Background on open source community and governance

Open models and communities

In the development of innovations, *openness* in exchange of information with external parties – companies (Chesbrough, 2003; Chesbrough & Appleyard, 2007), academia, or individuals (Benkler, 2002; Benkler & Nissenbaum, 2006) – is a powerful way to reduce development costs and accelerate innovation. The community studied here ranks high in openness using a metric developed by Bonvoisin & Mies – the 'Open-o-Meter' (Bonvoisin & Mies, 2018). This community coordinates volunteers' efforts to design an affordable portable ultrasound probe with a smartphone app to visualize images. This OSH project is the congruence of a medical and a technical project in which anyone can study, modify, make, distribute, and sell the hardware/software based on that open design/code (Winter et al., 2019).

Governing open source communities

The study of institutional arrangements to preserve shared resources started half a century ago with the seminal work of Elinor Ostrom. She described how a group of people could self-organize and create a commons to govern and preserve shared natural resources: CPR (Ostrom, 1990).

Starting in the early 1980s, a series of intellectual property rights laws and court rulings have progressively reduced the scope of 'open access' knowledge (Coriat & Orsi, 2002), for instance, software programs and living organisms have become patentable. Thus, emerging sectors such as Information Technologies and Pharmaceuticals have started to patent their innovations extensively. The legislator's initial intent to stimulate innovation by creating an incentive for companies to invest in new technologies eventually became an obstacle to the creativity of many innovators and communities. This second enclosure movement (Boyle, 2003) invited scholars to extend the concept of CPR to knowledge (Hess & Ostrom, 2003)

and to various digital assets, fruits of the internet revolution (Benkler & Nissenbaum, 2006; Bollier, 2008; Dedeurwaerdere et al., 2014; Laerhoven & Ostrom, 2007; Ostrom & Hess, 2007). Communities have become a central component of this decentralized production of digital assets, made possible by access to the internet and the reduction of transaction and replication costs (Benkler, 2006).

In this paper, we allude to open source communities or commons interchangeably. More precisely, a KC “refers to the institutionalized community governance of the sharing and, in some cases, creation of information, science, knowledge, data, and other types of intellectual and cultural resources” (Dedeurwaerdere et al., 2014). Knowledge is neither a well-bounded nor a straightforward concept; in this article, we consider knowledge as ideas, data, and information at any point in the wisdom hierarchy (Davenport & Prusak, 1998; Henry, 1974). To better describe the variability and complexity of knowledge and information as a resource, we extend the notion of knowledge to creative works (Ostrom & Hess, 2007).

In a commons, knowledge is considered to be a shared resource to be enriched and maintained (Coriat, 2011). For example, communities combine their resources to provide public libraries (Shuhuai et al., 2009). The scientific community 'stands on the shoulders of giants' as it makes advances in complex problems that no person or organization could solve alone (Spier, 2002). In sum, when people collaborate to share and produce knowledge, they create a KC.

KC constitutes a compelling mode of production of information, knowledge (Coriat 2011), and innovation since there is virtually no limit to the number of participants in a commons. It has proven to be a game-changer in the production and circulation of information while safeguarding innovators' intellectual property (Allen & Potts, 2015, 2016; Potts, 2017). Furthermore, Frischmann, Madison, and Strandburg have shown that norms, community standards, and democratized participation is an effective way to govern intellectual resources even in the absence of traditional intellectual property (Frischmann et al., 2014). Scholars have described countless

cases of virtual communities organized as commons that produce knowledge, in particular software (Hess, 2012; Ostrom & Hess, 2007; Schweik & English, 2012). However, the technological landscape has changed, and innovations made the creation of physical products considerably more accessible to individuals, such as Arduino, Raspberry Pi, 3D printing, and fab labs. Community members now work together to build complex tangible objects. However, building objects 'in the real world' is not as simple as writing a piece of code; extra constraints of the physical world will influence the KCs governance.

Scholars' understanding of open source community– as a KC – derives from the study of OSS communities. As OSH practice takes off (Pearce, 2017), it is crucial to assess the validity of our current models against the extra complexity brought by a product existing in the physical world.

A brief history of the open source movement

The open source movement started in the 1980s with Richard Stallman (Stallman, 1985), an MIT engineer frustrated by a software program not answering his needs. He realized that he was not allowed to make minor modifications without infringing copyright laws. He created an innovative software license: the GNU⁷ General Public License permitting modification, copy, and redistribution of software programs (Stallman, 1999; Stallman et al., 2002). This legal mechanism, known as *copyleft*, is the cornerstone of the OSS community's global success. This robust system of licensing promotes and protects OSS innovations, although, as we will further explore, this licensing mechanism is not fully applicable to OSH (Ackermann, 2009).

The open source approach has many virtues that scholars have analyzed over the past thirty years. It reduces project development costs (Gruber & Henkel, 2006; Schweik & English, 2012), brings innovation (Chesbrough, 2003; Schweik et al.,

⁷ The name “GNU” is a recursive acronym for “GNU's Not Unix.”

2005), and products created by a voluntary, global collaboration of people are regularly shown to be superior to proprietary solutions (Benkler, 2016; Redlich & Moritz, 2019). It is no longer a question of knowing whether open source is a rational choice or an emerging trend (Carillo & Okoli, 2008). It has become a mainstream way of developing novel technology (Pearce, 2017), e.g., as of July 2019: 86% of smartphones rely on Linux as their operating system⁸.

Introducing Open Source Hardware

The OSH movement is an extension of the OSS movement into the physical world (Raasch et al., 2009; Schweisfurth et al., 2011). The Open Source Hardware Association defines OSH as a tangible artifact “machines, devices, or other physical things – whose design has been released to the public in such a way that anyone can make, modify, distribute, and use those things” (OSHWA, 2020 Website <http://www.oshwa.org/definition>). In summary, an OSH product is a physical artifact whose documentation is released under a license granting production and distribution rights to anyone. This documentation has to be sufficiently comprehensive to enable anyone to build the object and develop it further (Bonvoisin, Mies, et al., 2017). For a long time, it has been considered a means to develop “gadgets for hobbyists” (Hansen & Howard, 2013). Unlike the products of software development projects, the products created by open hardware project communities are substantially more complex to organize and implement due to their tangible nature. They require a broader range of expertise and skills (Lerner & Tirole, 2005; Raasch et al., 2009), although technological evolutions such as 3D printing and fab labs in the last decade have helped to overcome some of these challenges.

The expected benefits of OSH are numerous: reduced cost of R&D, a faster innovation cycle, lower legal fees, better product quality, lower cost of repair, and

⁸ <https://www.idc.com/promo/smartphone-market-share/os>

an ethical bonus for the brand (Gibb & Abadie, 2014; Gibney, 2016). However, OSH is a relatively new movement, and the number of publications in the peer-reviewed literature is inevitably lower than the number of ongoing projects that are still in early phases (Pandey & Vora, 2019). The added value compared to the proprietary model is not yet fully understood (Huang, 2015). However, emerging literature tends to indicate that in the medical field, the return on investment is significant (Pearce, 2015a, 2015b).

Medical device regulation

Medtech projects have bloomed⁹ in recent years (Pearce, 2017) thanks to increased access to 3D printing and fab labs (Niezen et al., 2016). However, it is not clear how they tackle the challenges posed by the regulation of medical devices (EU, 2010). In regulated markets such as the US or EU, a medical device cannot be distributed legally without proving its safety, validated by a security clearance given by an appropriate regulatory body (Twomey, 2013). In Europe, this regulatory process is governed by the Medical Device Directive that describes how organizations could obtain the CE mark- a guarantee that the device complies with the applicable rules and regulations, and is safe and efficacious for patients.

Existing literature usually assumes that companies, startups, or academic labs manufacture OSH devices (Li & Seering, 2019; Pandey & Vora, 2019). But the emergence of the OSH movement in the medical field led the Food and Drug Administration (FDA), in charge of medical device certification in the United States, to change their policies. For instance, FDA proposed flexibility for smartphone-based applications (FDA, 2013) and 3D printing (De Maria et al., 2018; FDA, 2018).

However, simplification of the regulation does not apply to sophisticated medical devices such as the ultrasound probe under study in this paper. An ultrasound probe

⁹ Open MRI, open ecg, Bio nico, Raptor hand, Prosthetic hand, Robot hand

is a class IIa medical device; it must be assembled by a specialized industrial partner that grants a CE mark after validation by the notified body. Moreover, regulators require that the development and manufacture of medical devices comply with quality management guidelines ISO 13485 (Abuhav, 2018).

In a KC, volunteers enrich the pool of knowledge when they can, when they want, without constraints or commitment. They cannot be held accountable for complying with regulation within a quality management framework; a community cannot have its product authorized for commercialization¹⁰.

Hence our RQ: *How can Knowledge Commons adapt to industry regulations and place a product on the market?*

The KC we study in this paper faces severe challenges in complying with the regulation. We will pay particular attention to their self-transformation into a private entity without discouraging community volunteers or terminating the KC.

Protecting Open Source Hardware

Contrary to widespread perception, KCs are not growing based on an absence of rights (Hess & Ostrom, 2007). Instead, they are prospering thanks to different types of rights, allowing fit-for-purpose use, modification, and distribution. They protect authors and innovators who choose to make their work available for free to retain their copyrights. However, copyright does not protect ideas -or objects-, it protects the expression of these ideas; for instance, schematics or documentation of these ideas -objects- (Ackermann, 2009). Hence, typical copyrights and licensing originating from the OSS movement may not offer suitable protection of knowledge generated by KC in OSH (Marrali, 2014).

Usually, OSH projects are developed for a nascent or not existing market; therefore, the temptation for the third parties to free-ride the resource and enter these markets

¹⁰ <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32017R0745>

is low, protecting de facto the intellectual property of the innovation. In some cases, that could constitute “good enough” protection.

Another mechanism of protection is the patent. It is not part of OSH community ethos to patent; often perceived as an impediment to innovation (Bergsland et al., 2014; Chien, 2013). Compromises such as defensive publishing or patent pooling place the invention in the public domain to protect it (Beldiman & Fluechter, 2018; Schultz & Urban, 2012). In the absence of suitable protection -open access to knowledge but with clear ownership- the Common could be in danger; typically, a free-rider could decide to patent the knowledge obtained from the community.

3.3 Empirical analysis

3.3.1 Methodology

The study of a KC is a complex exercise (Madison et al., 2010) due to the dynamic nature of institutional arrangements and the wide variety of commons (Hess, 2008). Hence, we relied on the last version of the institutional analysis and development framework, adapted to take into account specificities of knowledge as a shared resource (Frischmann et al., 2014; Ostrom & Hess, 2007). The GKCF supports the identification of various 'building blocks' that make up the governance of a common. The first building block relates to the basic attributes of the KC, including resource characteristics, community members, goals and objectives, and rules-in-use. The second is the 'action arena' where choices made are governed by 'rules-in-use,' and relevant stakeholders interact with one another to deal with the social dilemmas associated with sharing and sustaining of the resource. The resulting pattern of interaction – how people interact with rules, resources, and one another – is described in Figure 3-1(Ostrom & Hess, 2007).

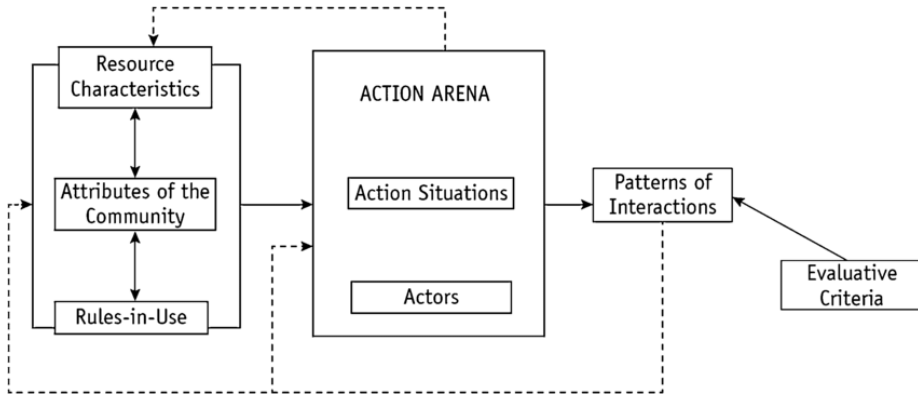


Figure 3-1: Governing Knowledge Commons framework (Frischmann et al., 2014)

Furthermore, GKCF provides a comprehensive approach to case study design and analysis, facilitating comparison with other cases to produce generalizable results. This exploratory case study approach is particularly relevant for analyzing changes and the reasons for them. Qualitative research is particularly adapted to our case, where our goal is to highlight the reasons for governance decisions within the KC (Yin 2010). We want to understand governance adjustments in response to social dilemmas arising in the development of an OSH medical device. An exploratory case study will allow us to gain an extensive and in-depth description of this social phenomenon (Merriam, 2009). We presume that these causal links are too complicated to be investigated by a survey or experiment. Moreover, we have no pre-determined outcome when asking 'how' or 'what' questions (Yin, 2014).

Empirical setup and data collection

In January 2020, we had access to the echOpen lab in the AP-HP premises in Paris for three days, where we conducted in-person semi-structured interviews and attended meetings as silent observers. The echOpen team granted us access to internal documentation. Since it is a very open community, most of the content was freely available over the internet on their website or even on their Slack application

– a digital workplace to organize team discussions and structure documents shared among members. This community information platform has been incredibly useful for coordinating with community members for internal document sharing. We were rapidly granted access to the development platform and became members within a few hours. We then proceeded to the archival analysis of internal documents, reports, and websites.

We first targeted core community members for an interview, since they are more knowledgeable in the governance mechanisms at stake. Then, we expanded to occasional contributors in the medical or technical field. We conducted fourteen semi-structured interviews with the core members of the community (the CEO of echOpen, founding partners, seconded staff from the funding partner, medical doctors, and academics). The average interview length was between 45 and 90 minutes. The questions were inspired by the GKCF research questionnaire and were tailored to the context. Our questionnaire was designed in English, although informants were allowed to answer in French to improve the quality of their feedback. Quotations in this paper are in English; when translated from French, we asked informants to confirm that the translated quotation faithfully transcribed their opinion.

For triangulation purposes, we collected secondary data from publicly available documentation over the internet, on the community's wiki, GitHub, website, and past newsletters.

For our data analysis, we transcribed more than 300 pages of interviews, which represents approximately 18 hours of recordings in French and English. We designed our questionnaire to fill in the GKC framework; our coding was deductive, resulting in the minimization of coding bias.

In the next section, we use the GKC structure to describe the echOpen environment and governance choices in light of the characteristics of the pooled resources.

3.3.2 Goals and objectives of the commons

Introducing a new paradigm in clinical examination

Echo-stethoscopy is the use of an ultra-portable ultrasound imaging or medical visualization tool to enhance the diagnostic orientation capabilities of health professionals during a clinical examination (Elezi, 2018). General practitioners, emergency physicians, specialists, midwives, and nurses can improve their diagnostic abilities and work routines (Narula et al., 2018). More frequent and affordable imaging during clinical examination benefits patients but also taxpayers, thanks to a reduced number of complementary examinations and faster patient management. Emerging literature is starting to study how echographic imaging or insonation can improve physical examinations (Narula et al., 2018).

The primary objective of the community under study is the adoption of echo-stethoscopy as an innovative medical practice. The distribution of a large number of probes to physicians and a growing community of healthcare professionals is contributing to this objective. A not-for-profit (NFP) association supports the community, and one of its bylaws¹¹ clearly states the community's goal:

Its purpose is to promote the general interest by the development of free software and open hardware projects which can benefit all and be reused or redeveloped by all, respecting norms and open standards, promoting virtuous digital practices, a free web, and guaranteeing the respect of personal data [...] more specifically in the field of health, by making accessible, open, affordable, and collaborative medical technologies, such as ultrasound imaging.

¹¹ echOpen bylaws, 2018

In this endeavor to change medical practice, conceiving an affordable and fit-for-purpose ultrasound probe is an essential part of the process. The mission statement further describes key deliverables:

Create a multidisciplinary community with a shared vision to create the first low-cost, open-source echostethoscope [...] document all the work done by the community and make it available to all those who want to run a free, open and collaborative project.

echOpen has a role in shaping the landscape of diagnosis and may well create a market that could attract private companies and create a virtuous circle. The business development manager states very clearly how they will assess and evaluate the progress of their mission:

The success factor is dissemination. So that we are able to [...] increase, develop the community. [...] One example is using this technology for veterinary purposes [...] disseminating even basic knowledge about ultrasound, about electronics, about everything, all subjects. For us, it is very important. [...] We [...] see us also as a platform developing knowledge about ultrasound, about echography, about medical imaging, about electronics, about software, et cetera.

Ultimately, with the dissemination of echostethoscopy as a metric to measure the success of the common, if a third party manufacturer reduced their prices to provide affordable probes, the echOpen mission would still be considered a success.

3.3.3 Community stakeholders

This KC is the epicenter of various stakeholders' efforts. First and foremost, the founders, pioneers in the medical community who believe echostethoscopy to be a giant leap forward for the practice of physical examination and diagnosis. Two of them are medical doctors at the Assistance Publique – Hôpitaux de Paris (AP-HP), one of which is specialized in radiology. The third founder is an open community and technology expert who has created numerous open data projects, including one dedicated to accelerating cancer research. They were rapidly joined by various software and hardware developers who wanted to help.

Along with them, a small group of very active volunteers started to dedicate an increasing amount of time to the project, close to a full-time equivalent. They joined the community highly motivated by the idea to build a low-cost medical device that could improve life of the poorest.

A software developer rapidly took the lead for the development of the smartphone app. Similarly, an electronics expert was appointed to take the lead for the electronic aspects of the probe. Likewise, an engineer was identified to integrate the probe's mechanical parts with the software and hardware.

A public health doctor joined the team to coordinate the pool of medical experts. Their role was to define the field of application of the echostethoscope, basically in which case the medical device is useful and how to interpret the results displayed on the screen. Organs are targets, and the community is interested in identifying what visible signs of a potential pathology are.

A project manager and community manager joined the common to help coordinate the community. We will refer to this group of ten to twelve members as the core team.

In parallel, an increasing number of students, universities, and engineering schools brought their research facilities and expertise to the common. An engineer from the core team observes:

I never imagined that I would be able to make a phone call or call on LIP6 experts to shed light on this or that communication issue. For example, some time ago, someone asked, “Do you have an expert who specializes in this or that communication protocol?” And we spent an hour discussing with that person in a meeting.

OSS projects can live and evolve during the early years of their development without physical infrastructure or external financing. However, the development of a physical artifact by the echOpen project required a commonplace to organize gatherings or meet-ups and, above all, a fully equipped lab to build and test prototypes. Thus in 2015, core team members created a French NFP association to support the development of the project. The AP-HP made premises available and lent equipment and decommissioned ultrasound machines for reverse engineering. Later on in 2015, the Foundations Pierre Fabre and Sanofi Espoir brought financial resources and dedicated staff to support the project. In 2017, Altran signed a partnership with the association to provide pro bono consulting. Finally, in 2018, echOpen joined the 'knowledge and innovation community' of the European Institute of Innovation and Technology (EIT) called EIT Health. This program provides financial support and access to a vast network of academic institutions and consulting firms.

At a later stage, an industrial partner was involved in manufacturing the final version of the ultrasound probe, based on the community's prototype. The ultrasound probe is a class IIa non-invasive medical device¹². The affixing of the CE mark by the designated manufacturer¹³, required for commercialization across the European

¹² Regulation (EU) 2017/745 of the European Parliament and of the Council of 5 April 2017 on medical devices

¹³ The commercial entity who takes responsibility for the manufacture of the product and is designated on the label. It is not necessarily the same entity which physically ‘makes’ the product.

market, is authorized by a Notified Body. An audit is conducted covering the conformity of the product's technical file and the manufacturer's quality system.

3.3.4 Resource characteristics

We do not really expect resources from the community. [...] Any organization that is interested in contributing can provide resources.

Co-founder

Several deliverables are needed to provide affordable echo-stethoscopes to healthcare professionals around the world successfully.

A low-cost ultrasound probe must be designed and produced, a smartphone app must be developed to visualize images received from the probe, a robust training program to ensure the probe is correctly used and images are understood correctly must be prepared, and finally, medical proof of the device's efficiency is required. These deliverables require a blend of specific skills provided by volunteers, pro bono consultants, freelancers, and pooled in the community.

The technical community's main objective is to design and deliver two work packages: the smartphone app and the low-cost ultrasound probe (Figure 3-2). The probe is a complex piece of hardware that transforms ultrasound waves sent into a patient's body into an electrical signal that is interpreted by the smartphone app, which reconstructs an image of the organ under investigation.



*Figure 3-2: echOpen Concept (picture on the left the probe, picture on the right the smartphone App)
©echOpen*

Business as usual: Building an open source app

The app transforms a smartphone into a visualization screen for the ultrasound probe. Building the app requires a broad range of expertise in software development and engineering skills, image processing, mobile apps, iOS, Android development, and low-level language programming. Developers interact online with the support of digital tools such as GitHub or Slack that facilitate code sharing and validation. They also meet during hackathons or other regular events.

Physicians and engineers collaborate closely during the development of these two apps. The medical community was in charge of the specifications and validation, while the technical community worked on the development. As a purely intangible asset protected by copyright laws, the code produced for the two prototypes is available on GitHub, fully accessible to the public. It is reusable under the BSD 3, a permissive license allowing unlimited redistribution for any purpose as long as the copyright and warranty disclaimer is not modified.

Welcome to the tangible world: Building the probe

The ultrasound probe work package is more challenging to execute, and with a large number of people involved in OSH design or development, it is a complicated endeavor (Boujut et al., 2019). The expertise needed is highly specific: Acoustic,

transducer and electronics experts are difficult to onboard (Lerner & Tirole, 2005). OSH projects require resources that are physical and subject to competition, as opposed to the purely digital resources of an OSS development project. A physical meeting place is needed to gather participants and build the prototypes. AP-HP lent a free lab where community members can come to work on prototypes. They have access to electronic equipment: oscilloscopes, electronic material, components, and a few prototypes. The relatively high cost of the prototype limited the number available for testing and development, turning community members into competitors; when someone works on a prototype, and others cannot:

echOpen lab is based at Hotel Dieu Hospital in Paris and is open to the public every day. To come, a simple mail is needed. We developed a fully documented ultrasound technology kit divided into modules. Each module corresponds to a category such as a transducer, mechanics, analog electronics, digital electronics, signal analysis and software application, etc. to let anyone with skills in such areas to get involved in an inclusive manner.

Introduction of echOpen Welcome Kit

Various academic institutions reinforced the technical community; among others, Lip6 Sorbonne specialized in onboard computers and in engineering EPFL - Ecole Polytechnique Federal de Lausanne or ULB - Université Libre de Bruxelles. They brought direct access to their researchers' networks, labs, and equipment that echOpen could not afford. A founding member comments:

Any organization that is interested in contributing can provide resources. Opening their facilities, as we had with schools, universities, and research labs gets us free access to their materials, their equipment that we could not afford.

Physicians, radiologists, and healthcare professionals contributed to the specification of the probe, including the expected features, design, and size. Professional designers helped to optimize the form factor and the size of the probe. The community's ambition is to place a probe in every doctor's pocket, replacing its famous ancestor, the stethoscope. Thus the probe should be relatively small and able to fit in a shirt pocket. The documentation and design of the prototype probe are publicly available under a GPL 3 license¹⁴ adapted to the hardware. However, this protection is partial and can easily be overcome with a few minor design modifications, potentially allowing third parties to patent it against the community to protect their market share. Hence, the community considered patenting some key elements of the device and make them available under an open license to secure subsequent open use and improvement.

3.3.5 Governing the commons

Rules-in-use

The 'rules-in-use' are governance rules that explicitly deal with the conditions for the enrichment of shared resources; they may be formal or informal. Although the community is five years old, there are no formal governance rules to govern the project development. The only formal rules that we discovered were in the bylaws of the association, which describe membership and the organization of their governance. We identified consortium agreements that govern project interactions between funders and the echOpen Foundation, which explicitly or implicitly push the association to work toward a specific objective. For instance, Sanofi Espoir would like to promote the use of the ultrasound probe for the benefit of children and maternal health.

There are a few informal rules that everyone follows: Budget-related questions are the co-founder's responsibility, medical questions are dealt with by a group of

¹⁴ <https://www.tapir.org/ohl.html>

doctors who are experts in the field, and software development is under the responsibility of the lead programmer. The decision-making process is very collegial, with a strong need to establish a wide consensus within the core team. In case disagreements cannot be resolved during the week, they are brought to arbitration at the weekly meeting every Monday. A co-founder summarizes the dynamics of these arbitration meetings:

There is one tacit rule, only one: [...] the one who is doing the work is right.

The action arenas

The *action arena* is the place governed by 'rules-in-use,' where relevant actors make choices and interact with one another to deal with social dilemmas associated with sharing and sustaining the resource. It is also the place where actors decide to make rules and norms applied to the Common that evolve to cope with emerging constraints.

The *raison d'être* of a KC is the enrichment and sharing of a resource (Coriat, 2011). The community makes choices in the action arena that are assessed against their evaluation criteria: to create knowledge and disseminate it.

Privatization to comply with medical device regulation: A social dilemma

During project development, the echOpen community had to overcome various social dilemmas within the action arena. However, complying with medical industry regulation is probably the most challenging dilemma they had to resolve (Madison et al., 2009).

A portable ultrasound device is considered as a medical device by the health regulatory authority in Europe¹⁵. Medical devices are grouped by *classes* designed to be representative of the level of risk associated with the intended use of the

¹⁵ Medical Device Directives (MDD): MDD 93/42/EEC; MDR 2017/745; AIMDD 90/385/EEC

device. These classes are defined by a set of rules based on different criteria, such as the duration of contact with patients, the degree of invasiveness, and the part of the body affected by the use of the device¹⁶. Active devices intended for direct diagnosis or monitoring of vital physiological processes are in Class IIa. Devices at this level are considered to be low to medium risk products. They require authorization from regulatory bodies to be used on patients and commercialized worldwide; FDA in the United States and Australia Therapeutic Goods Administration in Australia, for instance. EchOpen decided to obtain CE marking first due to their geographic location. Medical device manufacturing is controlled by certification of CE marking, following a conformity assessment process. The submitting organization, aka the manufacturer, must provide a technical compliance dossier and have it audited by a notified body. This certification authorizes¹⁷ the usage of the medical device on patients and its commercialization within Europe. The CE marking¹⁸ has no legal jurisdiction in LMICs. However, health authorities generally recognize that the technical dossier and quality audits that have been implemented for the European Conformity Assessment process are sufficiently sound to demonstrate the device's safety and effectiveness. These generally constitute a very significant part of the requirements for importation, with some country-specific administrative procedures.

Securing the CE certification process is a critical success factor for the echOpen project. Although an association or a community can outsource the production of the device to an industrial manufacturer, it cannot fully comply with the registration dossier.

Even if you are very highly engaged community, you will never attain CE marking for a medical device. When you have a community, even

¹⁶ Medical Device Directives (MDD): MDD 93/42/EEC; MDR 2017/745

¹⁷ Some member states require some other (administrative) steps such as registration with the national authority.

¹⁸ Like a clearance or approval from the FDA or any other 'major' regulatory body.

if [you] follow [a documentation process strictly], because you need to show the working contracts of the people [developing] the solution. When you have a community, you don't have a working contract, you don't have the resume [...] nothing has been put in place for a collaborative and even open project to achieve industrial goals. [...] a quality management system [...] cannot be on a voluntary basis.

Co-founder

Community work can hardly be placed in a quality management system: internal standard operating procedures are vague or non-existent, the association has no employee who can be contractually held responsible for quality control. In sum, OSH communities cannot put a medical device on the market.

This brings the commoners to the main decision point in the community's development: In order to achieve the association's mission, the community decided to create a private company. That was a turning point in the development of this KC since the original intent was to stay informal, open, and not to become a company.

A software developer observes the risk of enclosing the common:

You don't know what could happen on the way, that's always a risk [...] that you do not lose control of what you have done, that all the contributors that volunteered to do it, they [give] their works to a company that [...] make[s] money on the work of thousands of contributors because they host this thing or make it more accessible. That's super frustrating because, in the end, all these people that did it in their free time, they ultimately [have] been exploited.

The creation of a private company, in addition to the community, is a convenient way to scale up the development of the probe and to distribute it more rapidly. It becomes possible to approach venture capitalists with a business plan and seek extra funding, thus accelerating project delivery. In that sense, it fits with the objective of

the common: “disseminating the tool” as a prerequisite to disseminating medical knowledge.

However, this move toward privatization has a substantial impact on the hardware community's governance and culture of openness. While working under the umbrella of the private organization, free communication and information sharing outside the private entity will be on hold.

The common is in danger if volunteers do not follow the new strategic direction, since commoners' commitment is vital for the survival of the community (Ostrom 1999). Commoners perceive privatization as going against the ethos of an open hardware community and may become demotivated by this unintended privatization.

This strategic direction must be understood and agreed by all to avoid the tragedy of the digital commons – underproduction or lack of maintenance that ends up killing a project (Schweik & English, 2007).

Therefore the volunteers' two main concerns have to be resolved to maintain the involvement of the project's various stakeholders:

- How to resume the KC after the ultrasound probe industrialization phase?
- How to secure the open source nature of the knowledge produced by the common?

The private entity's role is to manufacture and sell the probe, but being able to resume the common after the manufacturing phase is a crucial part of the KC success. The community is the keystone of the product post-launch phase; members will develop the semiology, training material and become ambassadors of echostethoscopy. These crucial steps are instrumental in reaching a critical number of health professionals adopting this new medical practice and in triggering a snowball effect.

Hence, to secure the *Open source destination of the community* and the *resuming of the common*, echOpen has implemented a form of project portfolio management. A

new, fully open source project is started, and volunteers are invited to participate while the core teams and suppliers are working on the manufacturing phase of the ultrasound probe. This new project is EchOlab Box (ELB), a standalone 'do it yourself' kit based on the open source foundations of the ultrasound probe repurposed for educational ends. Students from schools and universities have access to a bundle containing simple step-by-step documentation, hardware components, and ready-to-use software to install on a smartphone. Together, in class with their teacher, they can build an ultrasound emitter and conduct experiments. This kit contributes to knowledge dissemination, reinforces the community's expertise in ultrasound technology, and is not subject to medical device regulation.

Meanwhile, the manufacturing of the ultrasound probe continues as a 'closed project' supported by consultants and suppliers. This project will remain closed and confidential until the development is completed and the probe available on the market. At that stage, all source code, schematics, and hardware design will be released into the public domain (Table 3-1). In the future, when developing a subsequent version of the probe, echOpen will continue with this pattern of alternating open and closed project phases, initiating a new open project for Version 2 of the probe that will, in turn, be closed at the industrialization phase.

		echOpen Project portfolio			
		EchOlab Box	Probe V1	Probe V2	Probe V3
Project Timeline	T1	N/A	Open Project	N/A	N/A
	T2	Open Project	Closed Project	Open Project	N/A
	T3	Open Project	Open Project	Closed Project	Open Project
	T4	Open Project	Open Project	Open Project	Closed Project

Table 3-1: Project openness evolution – Own elaboration

This agility of resources within a project portfolio helps to maintain momentum for the community members. It facilitates the Common resuming since it was not

stopped but only focused on something else. Besides, commitment to publish source code and schematics under an open license, once the probe is available on the market, secures the open source nature of the community. Thus, the involvement of commoners in the projects prevents the termination of the KC common.

These two critical governance decisions are the core solutions echOpen found to overcome regulatory-led dilemmas and to secure the future of the KC.

3.4 Discussion

3.4.1 Contribution

With this case study, we describe why and how the creation of a physical object subject to medical regulation influences the evolution and governance of a KC. We provide evidence that KCs, coupled with dynamic project portfolio management, are effective and resilient institutional arrangements in OSH project settings. KCs are flexible and scalable enough to protect and grow shared knowledge throughout the development process of a medical device. This case opens a new area of research at the crossroads of regulated environments and open source innovations, where partial privatization of the Common is a convenient way to achieve product development. The exploration of OSH fields subject to regulation is becoming increasingly relevant. Openness in hardware development helps build trust, is usually more reliable, and the reuse of standardized modules facilitates maintenance and training (Gibney, 2016; Niezen et al., 2016). Altogether, these benefits are particularly adapted to low- and middle-income countries, where medical equipment training and support are often suboptimal (World Health Organization, 1985; WHO, 2010).

OSH projects are also a means to lower product development costs, facilitate dissemination of innovation (Broumas, 2017), and accelerate mass adoption. KC-based projects also open doors to unexpected or unaffordable expertise. Nevertheless, they bring extra complexity in terms of governance compared to the classical closed model of product development – volunteers expect extensive transparency and consensus in decision-making (Ostrom, 1990). Moreover, regardless of their institutional arrangement, they cannot overcome regulatory barriers without staff and a legal entity.

The fate of knowledge commons in a regulated environment

In this case study, we have identified limitations to the scale-up and success of OSH projects. Regulation can impose constraints that an informal community cannot overcome in normal circumstances (Twomey, 2013) – although, during the COVID-19 pandemic, regulation has been adapted to allow usage of OSH medical devices¹⁹. A class II or above project must fully comply with current medical device regulations to ensure patient safety. This regulation assumes the existence of a legal entity with staff or consultants to endorse the responsibility of device manufacturing, something a KC composed of volunteers cannot easily achieve.

Communities developing complex OSH projects in a regulated environment must anticipate the regulatory stage. They have to implement a quality management system early on and train volunteers to maintain it. It is hugely challenging, but unless they successfully do so, they will only be allowed to deliver a prototype and they will never realize their ambition – the production and distribution of a safe medical device.

Furthermore, the intellectual property of an OSH community is partially protected by the copyright mechanisms that made OSS so successful. Solely relying on open source licenses exposes the common to a significant risk that the community's work would be patented against the community - in our case study to prevent the emergence of a low-cost actor in a nascent market. Defensive patents are a suitable protection, but require temporary restriction of information sharing within the community while a legal assessment is conducted.

¹⁹ <https://www.insideeulifesciences.com/2020/03/23/mhra-issues-specification-for-a-rapidly-manufactured-ventilator-system-for-use-in-hospitals-during-the-covid-19-outbreak/>

Our first finding, although counter-intuitive at first sight, is that partial privatization of the Common is appropriate to protect the common's work. In this case, privatization of intellectual property through the use of patents ensures the availability of an open license to the largest number of people and contributes to knowledge dissemination. Moreover, privatization is a proven solution for coping with regulation steps, guaranteeing that the community's efforts will move from a functioning prototype to a market-ready product.

However, this privatization may well destroy the common, which leads us to our second finding.

Going private to avoid the end of the commons

The tragedy of the digital commons is the underuse or under maintenance of the KC. And during privatization, this risk of terminating the common is high since development is kept confidential and is no longer available to the members.

Communities face two dilemmas when forced to stop their activities during temporary privatization. Firstly, they have to prevent the common from ending due to this unexpected transformation. Second, they have to reassure members that the common will eventually resume.

Our second finding is that a project portfolio management approach, which facilitates coordination and prioritization of tasks and resources across multiple projects and multiple workstreams, prevented a fatal outcome. This type of project management also allows the dynamic assignment of volunteers from one project or work package to another, according to each project's development stage. Moreover, it maintains momentum and involvement within the common. The involvement of volunteers in projects changes over time (Table 3-2), with more activity at the beginning and the end. As a consequence, commoners are motivated to work on

several projects within an OSH Common. The variety of projects facilitates the reallocation of volunteers, previously working on an OSH project subject to heavy regulation, to purely open projects, thus keeping the community active, evolving, and mutually enriching.

		Timeline T1	Timeline T2	Timeline T3	Timeline T4
Volunteer involvement	Project 1	+	-	+	+
	Project 2		+	-	+
	Project 4			+	-
	Project 4				+

Table 3-2: Volunteers dynamic involvement in the KC

A new field of research for knowledge commons

Contrary to a frequent misconception, a KC does not thrive in the absence of rights, quite the opposite is true (Hess & Ostrom, 2007); here we have a striking example of commoners agreeing to create a private legal entity to handle compliance aspects of medical device manufacturing. KCs have demonstrated their relevance and flexibility in the OSH environment, they bring the ability to dynamically adapt to evolving constraints while securing the long-term objective of enriching pooled knowledge. For open source community members, openness is not only a means; it is also an end in itself. In that sense, KCs provide an *arena* where a consensus can progressively emerge to close down a fully open model and eventually resume it. As OSH projects multiply in the coming years, scholars will have tremendous opportunities to examine how these communities are evolving at the frontier of the digital and the tangible worlds.

3.4.2 Limitations and suggestions for future research

This paper is a single case study, therefore, the conclusions of our findings will have to be corroborated by other work. The Medtech industry is highly regulated; further case studies in other regulated industries would undoubtedly improve the reliability of our findings. For instance, the impact of environmental regulations (RoHS²⁰) or electromagnetic compatibility (the US Federal Communications Commission²¹) will most likely have a strong influence on the Commons' governance of other projects.

Our study was limited in time, so we did not witness the post-industrialization phase when the common resumed after the market launch. We could only record the intentions of the core team and the community; further research and a longitudinal case study on this KC would certainly bring valuable insights.

We witnessed that introducing a form of portfolio project management in a KC is an effective way to maintain momentum within a community. However, in our case study, only a handful of projects were managed in parallel. Further research is needed to understand the effect of breaking down the community into many sub-projects. The very existence of the KC could be endangered by potential divergence in the objectives of these subgroups. Besides, volunteers could lose interest in the project and leave the community.

The medical device landscape

Theoretically, NFP associations can manufacture medical devices with a CE marking. However, to the best of our knowledge, there is no such example and the literature is often very evasive on the regulatory question. This situation may change

²⁰ http://ec.europa.eu/environment/waste/rohs_eee/legis_en.htm

²¹ <https://www.fcc.gov/oet/ea/eammeasurements.html>

in the light of the recent COVID-19 crisis, which has shined the spotlight on the flaws of the “normal” way of validating medical devices built by communities. Regulators and communities have been able to respond to this emergency²² situation as volunteers worldwide have gathered as communities to produce masks, ventilators or spare parts for medical equipment. Henceforth they will need to focus on longer-term collaboration to amend a system that has been designed for corporations and requires adjustment to support the blooming of OSH communities building medical innovations.

OSH is a fast-paced emerging practice. Additional work is needed to define standards, influence regulatory bodies, and provide guidance on effective governance mechanisms to embrace its potential fully. We hope our work will help future OSH communities to anticipate the necessary transformation they will face as they progress along their product development pipeline.

We invite academics to conduct a longitudinal study of the entire development pipeline to gain a comprehensive understanding of the long-term dynamics of an OSH KC. This paper covers only phases T1 and T2 of the timeline in Table 3-1 , covering project development from inception to the end of the industrialization phase. During our investigations, we collected evidence that the KC will be instrumental in the launch and post-launch phase of the project (T3). For medical purposes, the community will collect data in order to be able to run clinical trials with the probe. Moreover, to help define how the probe should evolve in response to new needs, a user innovation approach will be followed (Hippel & Krogh, 2003). This stage deserves a more in-depth analysis to understand the transformation of the commons membership from 'commons-based peer production' (Benkler & Nissenbaum, 2006) to 'user-based innovation' (Hippel & Krogh, 2003).

²² <https://www.fda.gov/medical-devices/emergency-situations-medical-devices/emergency-use-authorizations-medical-devices>

With this case study, we identified profound institutional changes, starting with the creation of a NFP association and then later the birth of a private organization. These modifications raise a broader methodological question, how to study the evolution of KC over a long period (Strandburg et al., 2017)?

Finally, we hope that using the GKC framework will allow the comparison and aggregation of case studies from different industries and knowledge domains to shed light on the underlying contextual reasons for any differences.

4. Understanding individual motivations among members of online communities²³

4.1 Introduction

Since the emergence of the Internet, we have witnessed the blooming of web-based knowledge sharing and community peer production. OSS and OSH communities (Hausberg & Spaeth, 2020) have pushed the limits of what volunteers can achieve together. Countless success stories have demonstrated how a committed group of people – a community – can produce and share knowledge on specific topics, even in the legal field (Wasko & Faraj, 2005). As Benkler (2006) stated, the marginal cost of production and distribution of digital assets is close to zero, offering endless possibilities for individuals to exchange and produce new knowledge. A famous example is Wikipedia, but myriads of smaller websites are references for specific areas of expertise. Often, these websites have no commercial purpose and rely on volunteers to produce and moderate content that makes them thrive and grow.

Today, the overwhelming quantity of valuable, freely available content has profoundly changed our way of searching for and accessing information. This game-changing paradigm has led to numerous publications²³ over the past two decades (Alexy et al., 2013; Benkler, 2006; Hausberg & Spaeth, 2020). However, the literature tends to consider that a homogenous group of contributors powers these online communities. With this paper, we intend to demonstrate that this assumption is erroneous.

Recent work on social media and OSS has articulated a more fine-grained repartition of roles within these communities (van Mierlo, 2014). A pattern is emerging for

²³ This chapter has been published under the following reference. Carpentier, P. (2021).

Understanding Individual Motivations among Members of Online Communities. *Les Cahiers du numérique*, 17, 153–183. DOI: <https://doi.org/10.3166/LCN.2021.006>

online communities: A small proportion of members contribute most of the content, a few actively participate, and the majority merely read content without further interaction.

This paper aims to shed light on the differences in motivation for sharing knowledge between the major and minor contributors to a WKC. We conducted an online survey to assess their motivations to share acquired knowledge with the community. We performed SEM to validate our model and compare our results for these two groups. As a result, we formulated a series of hypotheses to help answer the following question: *Do individual motivations influence knowledge sharing differently for the two groups observed within web-based knowledge communities?* Furthermore, to get a more nuanced picture of individuals' motivation, we relied on SDT (Deci & Ryan, 2002). This theory describes how extrinsic motivations can be internalized and integrated into individual value systems under certain circumstances. This theory sheds light on how, progressively, involvement in a community affects the nature of individual motivation (Fang & Neufeld, 2009) and why sometimes community-related coproduction can be considered a lifestyle when fully internalized (Spaeth & Niederhöfer, 2020). Identification with the community values and objectives becomes a motivator to actively participate. So, we introduce a novel construct to the corpus of commonly agreed upon factors that influence people's participation in online communities: motivation through identification with the collective goal.

Our study makes two contributions. First, we confirm that various actors in WKCs have different motivations for knowledge-sharing. This reinforces the importance of targeting community management strategies to boost online activity, and we make propositions based on our results. Second, we found that individual identification with the community goal is the predominant motivator to active participation in online communities.

We organized this paper as follows. First, we introduce the concept of a WKC, discuss the structure, and consider the key issues related to community members'

motivation to share knowledge. Then, we rely on SDT to develop a model for examining how individual motivations impact knowledge contribution within the community. We test this model empirically through a survey collected from one electronic network of practitioners dealing with issues of ecology and sustainability. Finally, we discuss how our empirical findings contribute to theory development and improve our understanding of how knowledge exchange can be improved in WKC.

4.2 Theoretical background

4.2.1 Web-based knowledge communities

With the emergence of the Internet, people have started to gather online to interact on topics of interest; they form communities to build artifacts (Benkler, 2002b) or exchange ideas, and create new knowledge (Ostrom & Hess, 2007). They usually rely on online platforms such as social networks or websites to communicate and post content. Often the content created is directly available for consultation over the Internet with or without restriction. At other times a membership fee may be requested. Likewise, in companies, similar behavior is encouraged to foster knowledge sharing and value creation; in this case, computer-mediated communication is supported by an intranet or company portal (Ardichvili et al., 2003; Wasko & Faraj, 2000).

An online community is a broad concept that largely depends on the level of social interaction within the community. When social interaction is intense and the domain well-identified and sustained, it is usually described as a virtual community of practice – “online social networks in which people with common interests, goals, or practices interact to share information and knowledge, and engage in social interactions” (Chiu et al., 2006).

When participants are more interested in the content, and social ties between members are weaker, they exchange online within a WKC, “a community that allows individuals to seek and share knowledge through a website based on common interests” (Lin et al., 2007). A famous example would be Wikipedia, where knowledge creation is barely motivated by social interaction (Nov, 2007). The platform itself is described as an information system, not a social network (Yang & Lai, 2010). Typically, no recognition system is embedded in the online platform to promote individuals over content (Schroer & Hertel, 2009).

The main challenge for an online community is to nourish their members' willingness to contribute – i.e., share knowledge with others (Chiu et al., 2006). The life and death of an online community is linked to members' active participation and to enough site visits to generate the minimum revenue needed to secure maintenance of the technical platform (Schweik & English, 2007). Therefore, understanding what motivates members to participate and identifying effective incentive mechanisms is essential for their survival (Ardichvili, 2008; Ardichvili et al., 2003).

From a historical standpoint, the central question about online community and content creation has been “why do people spend their valuable time and effort contributing knowledge and helping strangers?” (Wasko & Faraj, 2005). In this paper, we refine this question since the described behavior does not represent the majority but a minority. The vast majority of community members just take advantage of the knowledge resource and never contribute. It is essential to analyze these two populations separately to understand their respective motivations better. Thus, we will first describe the structure of an online community. Then, we will turn to the extensive literature on the topic and SDT to identify relevant individual motivators.

4.2.2 Structure of an online community

We have adapted the OSS onion-like organization model (Crowston & Howison, 2005) to represent the various layers of a WKC; at the core of this informal

organization, there is a small team of very active members. The proportion of active contributors reduces as layers get further from the community core. This model has also been empirically verified for OSH communities (Bonvoisin, Thomas, et al., 2017). A rule of thumb, called the 90-9-1 principle for online communities, describes the following: 1% are super contributors, 9% edit and review, and 90% just read. Coined by Ben Mc Connell and Jackie Huba, this empirical principle has been confirmed by scholars (van Mierlo, 2014). However, the shape of the distribution is still debated (Carron-Arthur et al., 2014).

Community members have different roles within a community and contribute differently to knowledge production, depending on their expertise and willingness to do so (Madanmohan & Navelkar, 2004). To study a WKC, we have adapted the seven roles of the original OSS onion model to the following four roles (Figure 4-1): **Site visitors** are passive users consulting articles on the website. They are considered to be at the boundaries of the community. Sometimes called lurkers, they are invisible to other members. However, their relationship with the community may evolve, they may become members or experts (Von Krogh et al., 2003). They may advocate for the community's work, apply what they have learned, invite relatives to visit the website, or never revisit it. Due to the difficulty of reaching them, we exclude them from this study and instead focus on site members.

Members or peripheral members are site visitors registered to the website. They created a user profile with a login and password. They receive the community's newsletter, they can comment on articles, propose new content, or ask for clarifications.

Topic experts create new topics and answer members' questions and comments. Usually, experts cocreate articles with the core team to help them explain their expertise in a simple form.

The core team or core organizers often comprise one or more founders that initiated the community or the website. They are responsible for the vision and

overall direction. They also coordinate the website’s development and its content and are in charge of the technical maintenance of the platform and associated costs.

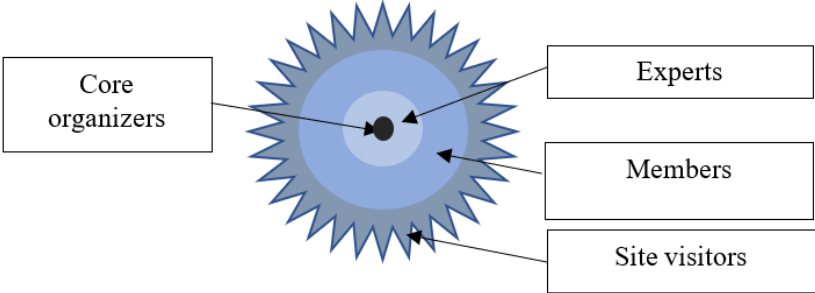


Figure 4-1: Adaptation of the onion-like model of organization (Crowston & Howison, 2005)

4.2.3 Knowledge sharing and motivations

In this article, we define knowledge sharing as an interaction involving the exchange of experiences, skills, and knowledge. It is composed of two main sharing processes: one based on the willingness to communicate actively and to “donate knowledge” and the second based on active participation in the exchange to “collect knowledge” (Ardichvili et al., 2003; van den Hooff & de Ridder, 2004).

We rely on motivational theory, a widely used perspective to study individual behavior, to understand the motivators underlying knowledge-sharing behavior. The term 'motivation' is defined as a psychological force that determines the individual level of effort and persistence when facing an obstacle (Kanfer, 1990). It cannot be directly measured; however, the outcome of motivation is behavior (Mitchell & Daniels, 2003) that we can measure using a survey. We intend to infer motivation from a continuous stream of behavior observations. Applying this model of motivation to a WKC can identify which factor motivates individuals to participate in knowledge-sharing activities (Osterloh & Frey, 2000).

Psychologists have developed multiple theories to conceptualize sources of motivation. Over the past decades, these theories have resulted in an increasing

number of empirical studies that analyze behavior in the field of information technology (Davis et al., 1992). Consequently, literature on the motivations for sharing knowledge within communities is abundant; it was initially developed to understand the open source movement (Alexander Hars, 2002) and why individuals would code software for free (Lerner & Tirole, 2002). This literature grew and expanded to WKC, with the success of Wikipedia and Wikipedia-like communities (Nov, 2007; Schroer & Hertel, 2009). The emergence of makers and OSH communities recently renewed the interest in understanding individual motivations to share and exchange knowledge and expertise (Hausberg & Spaeth, 2020).

Over the years, and across diverse community objectives, scholars have identified various factors affecting individuals' willingness to share knowledge in virtual communities or organizations, such as the enjoyment of completing a task, the pleasure of helping others, and knowledge self-efficacy (Kankanhalli et al., 2005). Complementary research described other significant motivators, such as financial rewards, incentive systems, peer recognition (Alexander Hars, 2002), own-use value (Choi & Pruett, 2015), cost-benefit assessment (Roberts et al., 2006), and the ease of using technology (Hall, 2001).

In sum, these antecedents for knowledge-sharing belong to two main types of motivators: intrinsic and extrinsic (Hsu et al., 2007; Lin, 2007; Wasko & Faraj, 2005). Therefore, to build our conceptual model, we relied on validated constructs belonging to these two groups. However, SDT describes a third kind of motivation when individuals integrate extrinsic motivators and make them almost internal (Deci & Ryan, 2002). This theory suggests that the regulation of extrinsically motivated behaviors can become increasingly internalized if the individual feels autonomous, competent in effecting a task, or socially related to the task's objective (Dedeurwaerdere et al., 2016; Ryan & Deci, 2000). For instance, one may feel that recycling garbage is an extrinsically motivated behavior – I recycle; otherwise, I will be fined. However, over time, this behavior can increasingly become internalized until the individual becomes almost intrinsically motivated and

potentially recycles with zeal – I recycle because I support the results of my efforts. The following factors are typical internalized extrinsic motivations in online communities: reputation, reciprocity, learning, and own-use value (Von Krogh et al., 2012).

Hence, we supplemented our conceptual model with additional factors from SDT theory literature. Our objective is to assess whether motivation through identification – when values are endorsed, fully internalized, and considered their own – can significantly influence knowledge sharing within a community (Ryan et al., 1995).

4.3 Research model and hypothesis

4.3.1 Intrinsic motivation

Intrinsically motivated people act for their pleasure, and their participation in a task is sustained by their enjoyment in completing it. Usually, they learn new things and are genuinely interested in what they do and learn within the virtual community (Deci & Ryan, 2002).

4.3.1.1 Enjoyment from helping others

Intrinsic enjoyment from helping others without expecting anything in return is a form of altruism (Smith, 1981). Knowledge contribution can be led by the desire to help others (Davenport & Prusak, 1998). Furthermore, contributors usually gain satisfaction when doing so (Wasko & Faraj, 2000). A notable example of this effect has been studied within the Wikipedia community (Yang & Lai, 2010; Zhang & Zhu, 2006). Participants' intrinsic motivation is a key motivating factor to contributing to this open encyclopedia, to the hacker community (Lakhani & Wolf, 2005), or in OSS development. Regardless of the type of online community, Lin showed that sharing knowledge correlates with intrinsic motivation (Lin, 2007).

In this online community, experts contribute significantly to creating content with the core team's help. Their contribution is voluntary; therefore, we expect them to be positively motivated by the enjoyment of posting articles and sharing knowledge. The same mechanism should apply to members who submit questions, comments, cast doubts on experts, and propose further ideas for online course creation.

H1a: Enjoyment in helping others is positively related to Expert knowledge-sharing behavior.

H1b: Enjoyment in helping others is positively related to Member knowledge-sharing behavior.

4.3.1.2 Knowledge self-efficacy

The feeling of competence, also known as knowledge self-efficacy, is someone's perception of their own ability to achieve specific goals with their skills (Bandura, 1986). For instance, when a member shares valuable expertise to the community, they increase their confidence. Their perception of themselves is improved with this increased self-efficacy (Constant et al., 1996). This generates a self-motivation that drives people to continue to contribute and share knowledge within the online community (Bock et al., 2005) or in a computerized system (Kankanhalli et al., 2005).

Community members who feel competent (Lin, 2007) or think their contribution could be valuable to others in a problem-solving environment (Constant et al., 1996) share knowledge more easily.

H2a: Knowledge self-efficacy is positively related to Expert knowledge-sharing behavior.

H2b: Knowledge self-efficacy is positively related to Member knowledge-sharing behavior.

4.3.2 Extrinsic motivation

Extrinsically motivated people are motivated by the results of their actions. This is a goal-oriented motivation, where one's behavior is motivated by the anticipation

of a future direct or indirect monetary compensation or an improved reputation (Deci et al., 1975).

4.3.2.1 Material gain expectation

The Lowimpact website does not pay experts to provide content. However, the experts sometimes run their own companies and certainly expect a return on their investment for their publications (Kankanhalli et al., 2005). For instance, they can expect an indirect payoff due to increased visibility gained when publishing on the website (Hall, 2001).

In terms of motivation, direct or indirect rewards under the form of a bonus, gain sharing, are an effective way to incentivize people to share knowledge, particularly in organizations (Bartol & Srivastava, 2002; Beer & Nohria, 2000; Hall, 2001). In online communities (Lerner & Tirole, 2002), developers estimate their level of involvement based on a cost-benefit analysis. As long as this involvement is beneficial, they continue to contribute to code development. This evaluation takes into account immediate and delayed payoff. Similarly, Lowimpact experts can be paid to produce knowledge and use the website as a promotion platform for further paid services and advertisement to reach out to new potential customers. Direct and indirect rewards are two types of extrinsic motivation known to influence the willingness to share knowledge in an online community (Hall, 2001).

Lowimpact promotes sustainable living, frugal innovations, and system change. These topics are potent levers to reduce environmental impact and also to save money for the community members. Website members may be extrinsically motivated by the expected savings made as a consequence of their participation in the online community.

H3a: The material gain expectation is positively related to Expert knowledge-sharing behavior

H3b: The material gain expectation is positively related to Member knowledge-sharing behavior.

4.3.3 Internalized extrinsic motivation

Understanding intrinsic and extrinsic motivations brings insight into people's reasons for participating in knowledge sharing. However, according to SDT (Deci & Ryan, 2002), extrinsic motivations can be internalized by an individual into personally endorsed values, thus assimilating behavioral regulations that were initially external. This internalization process is facilitated when individuals experience support for their competence, feel autonomous, and experience relatedness to what they are trying to achieve. These conditions are met in the lowimpact community, and we will describe what Deci and Ryan refer to as internalized extrinsic motivations (Deci & Ryan, 1987).

4.3.3.1 Reputation gain

For a WBK participant, there are two potential types of reputation they can gain, i.e. “peer reputation” and “outside reputation” (Von Krogh et al., 2012). Peer reputation is directed toward peers within a community; typically, a gain in reputation after a substantial contribution demonstrates one's skill or abilities (Raymond, 1999). For instance, in a corporate environment, experts and employees want to stand out from the crowd and be recognized by their peers for their expertise (O'dell & Grayson, 1998). If they succeed, they will benefit from increased prestige in their work environment (Kankanhalli et al., 2005; Kollock, 1999).

Outside reputation takes its roots in one's motivation to impress people outside the community and to expect a potential return in terms of prestige (Von Krogh et al., 2012). Outside reputation is a strong motivator to develop OSS (Roberts et al., 2006), being registered as a key contributor of a famous open source project can lead to substantial career advancement (Spaeth & Niederhöfer, 2020).

For Members, gaining knowledge online and sharing it digitally or in the real world with friends and colleagues also contributes to improving their outside reputation on specific topics (knowledge acquired on the website).

H4a: Gaining reputation is positively related to Expert knowledge sharing behavior.

H4b: Gaining reputation is positively related to Member knowledge sharing behavior.

4.3.3.2 Identification with the collective goal

The internalization process transforms an extrinsic motive to complete a task, e.g., sharing knowledge about ecology, into a personally endorsed value. Hence, the behavioral regulation that was initially external is assimilated into an integrated extrinsic motivation.

Legault highlighted the importance of two factors for internalizing a behavior regulation: understanding the regulation and its significance for the individual. Somehow a regulation has to echo people's values, needs, or behaviors (Legault, 2017). In our case, the regulation is associated with the constraints of editing and producing content for our experts. For members, the regulation is the extra constraints necessary to obtain actionable knowledge to elaborate a product or a service instead of merely buying an equivalent commodity at the corner shop.

This psychological mechanism has been demonstrated in the education sector, where better regulation integration leads to better grades for students (Vansteenkiste et al., 2004). Similar mechanisms have been seen in the acceptance and integration of a weight-loss program (Silva et al., 2010), and in the long-term participation in sports (Pelletier et al., 2001).

The internalization of extrinsic motivations is also at play in environmental activism. It leads to more actions for the planet and sustainable development, even if this requires additional effort compared to not acting sustainably (Green-Demers et al., 1997). In ecology, identification with the collective goals of conservation policy is a strong driver for sustainable behavior (Dedeurwaerdere et al., 2016). "The group goals become incorporated into the value system of the individual and

form the motivational basis for cooperative behavior”(Hemetsberger & Pieters, 2001), in particular for voluntary work or contributions to charity.

Within the Lowimpact community, members and experts are more likely to share their knowledge on the website if they adhere to, and internalize, the sustainable development values that the community promotes online (Ryan & Deci, 2000).

H5a: A higher level of identification with the community’s collective goal will positively affect Experts’ knowledge-sharing behavior.

H5b: A higher level of identification with the community’s collective goal will positively affect Members’ knowledge-sharing behavior.

4.3.4 Conceptual model

We measured the effects of our constructs on a group of Experts and a group of Site Members. We expected that the intensity of the effect of these constructs would vary from one group to the other.

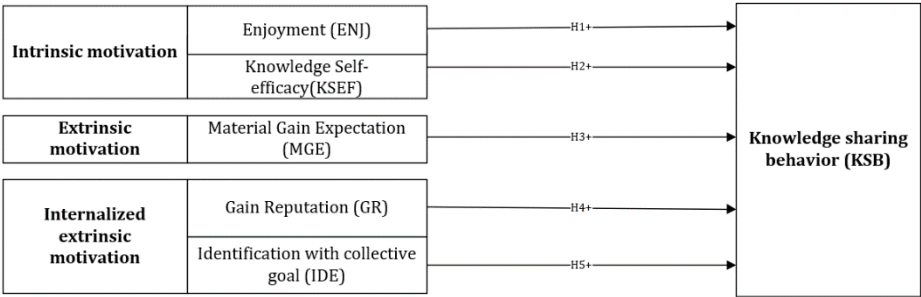


Figure 4-2: The conceptual model

4.4 Research method

4.4.1 Sample and measurement development

To test our hypothesis, we surveyed subscribers and experts of a WKC that focuses on “sustainable living resources” that intends to “connect lifestyle and system change” (Lowimpact website, 2020).

The Lowimpact.org website covers more than 220 topics ranging from mushroom cultivation to bow making and cryptocurrency. The site accounts for more than 50,000 visits per month and has become the reference source for specific topics such as compost toilets, solar panels, and straw-bale buildings. When a topic is the source of numerous discussions and many visits, Lowimpact can, with the help of experts, create online courses or publish a book. Lowimpact.org was created in 2015 – previously, it was a physical community. Knowledge sharing on the Lowimpact website is not based on social interaction; the platform is an intermediary, complemented by online videos, blog articles, and comments sections. Experts produce the vast majority of the content, which is consulted by a large population of members and anonymous visitors. They can both read and comment on existing articles. However, website visitors are entirely anonymous. Therefore, we targeted newsletter-registered community members with an online profile on the website. Our measurement items are adapted from the literature or from definitions provided by the literature. The survey was tested with five Lowimpact Experts, and core members of the Lowimpact website to assess its understandability and relevance. The comments collected led to several minor modifications of the wording and item sequence.

The dependent variable in this study, knowledge-sharing behavior (KSB), is assessed to indicate the motivation of an individual to share knowledge. For each survey item, informants were asked to assess their degree of agreement with statements on a 7-point Likert-type scale (ranging from 1 = *strongly disagree* to 7 = *strongly agree*). We also asked them to provide some demographic information.

4.4.2 Data collection

We designed two almost identical surveys: one for Lowimpact Experts and one for Members of the website. We added three questions to the introduction of the member's survey to make sure our two groups are mutually exclusive. These additional questions helped identify Experts who might have inadvertently followed

the newsletter survey link designed for Members. We redirected six experts to the correct group.

We sent our member survey to 9,064 registered members of the website and the expert survey to eighty-seven topic experts. To increase the response rate, we created a dedicated blog page explaining the objective of this survey. This blog²⁴ article was presented to the community through the monthly newsletter, and both pointed to the survey.

Respondents were offered participation in a draw to win a free online course on the Lowimpact website. We conducted two online surveys from January 31, 2021 to March 14, 2021.

Experts ($n = 87$) were contacted individually by the Lowimpact community manager to improve the response rate. That resulted in fifty-three answers, a response rate of 61% (see Table 4-1).

We sent 9,064 emails to members of the Lowimpact website, 2,082 emails were opened, leading to 709 members starting the survey. Some 481 members completed the survey while 220 did not complete it, and 8 declined the consent form.

	<i>Experts</i>	<i>Members</i>
Emails sent	87	9064
Emails opened	N/A	2082
Valid Survey Responses	53	467
Response rate	60.9%	5.3%

Table 4-1: Online survey response rate

After discarding the surveys with multiple missing values or unengaged respondents, 520 were usable for statistical analyses. For those records where less

²⁴ <https://www.lowimpact.org/help-lowimpact-become-wiki-survey>

than 3% of the values were incomplete, we replaced the missing values with the median for ordinal scales and the mean for continuous scales.

4.4.3 Demographics

We asked informants to specify their age, gender, education, current job position, and tenure on the Lowimpact website. A majority of respondents were females for the member survey (51%) and males for the expert survey (60%). Globally for our two surveys, 244 respondents were male (49%), and 252 were female (51%); for more details, see Table 4-2. We conducted an independent samples t-test to compare all our constructs in Male and Female conditions. There was a significant difference for Identification with the collective Goal (IDE) and Knowledge self-efficacy (KSEF), so we introduced gender as a control variable in our model for this study. According to our demographic results, Experts are business owners or independent consultants. Almost half of them (47.2%) have been involved with the Lowimpact community for more than five years, i.e., since the website's inception in 2015. Experts are younger than the average community member; 49% are above 50 years old. Thus, we decided to add a control variable to account for informants' duration of participation in the community and for participant age. They also have a high level of education (92% have a bachelor's degree or more).

Website members are older than experts, 72.1 % of them are 50 years old or more, and their education level is more normally distributed, with a majority having a bachelor's degree. Members discovered the site more recently than experts; 15% discovered it during the past year, while 39% have been involved since its inception. For both groups, a large proportion of respondents have been involved in the community since its inception (Experts 47 %, Members 39%).

	Experts		Members	
	(n = 53)	%	(n = 457)	%
<i>Gender</i>				
Male	32	60.4	212	46.4
Female	20	37.7	232	50.8
N/A	1	1.9	11	2.4
<i>Age</i>				
21–30	0	0	4	0.9
31–40	9	17	41	8.9
41–50	18	34	81	17.6
51–60	16	30.2	141	30.7
> 61	10	18.9	189	41.4
<i>Education</i>				
Junior High school or below	0	0	10	2.2
Senior High school	4	7.5	93	20.4
Bachelor's degree	26	49.1	193	42.2
Master's degree or higher	23	43.4	142	31.1
<i>Position</i>				
Self-employed/Consultant	15	28.3	169	36.8
Employee	2	3.8	100	21.9
Manager	2	3.8	39	8.5
Director/Business owner	34	64.2	62	13.6
Looking for a job	0	0	34	7.4
<i>Tenure in Lowimpact (years)</i>				
< 1	3	5.7	69	15.1
1–3	13	24.5	111	24.3
3–5	12	22.6	93	20.4
> 5	25	47.2	179	39.2

Table 4-2: Respondents' demographic information

4.5 Measures

To conduct meaningful SEM, we proceeded to exploratory factor analysis (EFA) and confirmatory factor analysis (CFA). This allowed us to propose a structural model and interpret our results.

4.5.1 Exploratory factor analysis

First, we conducted an EFA to verify and clean our factors for the subsequent SEM. Pattern matrix Cronbach's alphas are available in Annex - Table 7-1.

4.5.1.1 Adequacy assessment

Our principal component analysis with Varimax rotation yielded six factors explaining a total of 73% of the variance for the entire set of variables. A Kaiser-Meyer-Olkin test for sampling adequacy score of .840 was considered adequate (Kaiser, 1974). The successful Barret test of sphericity, with a significance of .001, indicated that our variables relate sufficiently to each other and that we could proceed with the EFA.

4.5.1.2 Validity assessment

Convergent validity checks if two measures that should be related are related. Our items load to the same factor, as predicted by the theory.

We confirmed the convergence validity, with all our factors loading above .7, except for one loading at .599 (KSB5). As evidence of discriminant validity, we did not find signs of cross loading; all other factor loadings were below .3 in the rotated component matrix (see Annex – Table 7-1).

4.5.1.3 Reliability assessment

We confirmed that our constructs were reliable and displayed internal consistency by using Cronbach's α coefficient. Each subscale's validity was confirmed, having a value of between .79 and .91, above the recommended threshold of .70, (Nunnally, 1978).

4.5.2 Confirmatory factor analysis

We conducted a CFA to confirm the factor structure extracted in the EFA. We verified that our proposed measurement model and our data for this study fit adequately.

4.5.2.1 Model fit

To assess the structural model fit, we calculated the ratio between χ^2 and the degrees of freedom, and obtained a result smaller than 3, the acceptable threshold (Bagozzi & Yi, 1988) ($\chi^2 = 273.7$, $df = 140$) $p < .001$.

Other fit indices confirmed a good fit for our model. The comparative fit index (CFI) was .975, above the .95 threshold. The root mean square error of approximation (RMSEA) was .043, considered to be an acceptable value (Browne & Cudeck, 1992) and our standardized root mean squared residual (SRMR) was inferior to .09 (Bentler, 1995).

The Tucker Lewis index (TLI) was .969, superior to the recommended value of .95, and the incremental fit index (IFI) was .975, superior to the acceptable threshold of .90; both confirm a good fit (Hu & Bentler, 1999).

Although our model goodness-of-fit (GFI) was .949, smaller than the recommended threshold by Hu and Bentler, it still met the requirement suggested by (Baumgartner & Homburg, 1996), (Browne & Cudeck, 1992) and (Doll et al., 1994): the value is acceptable if above .8.

4.5.2.2 Validity and reliability

We calculated the composite reliability (CR) to measure our model reliability; all our constructs had a CR value above .07, which is considered acceptable (Fornell & Larcker, 1981).

We then checked the average variance extracted (AVE) for our constructs to test their convergent validity (Table 4-3). All AVE values were above the recommended level of 0.50, except the IDE construct, with a close but inferior value of .493. In that case, since its CR value was higher than 0.6, the convergent validity of the construct was still considered adequate (Fornell & Larcker, 1981).

Finally, we assessed the discriminant validity by ensuring that the square root of the AVE for a construct was greater than the inter-construct correlations in Table 4-3.

We also ensured that the maximum shared variance (MSV) for each construct was inferior to its AVE (Hair et al., 2010).

Therefore, we can conclude that there is adequate internal consistency and reliability.

	<i>CR</i>	<i>AVE</i>	<i>MSV</i>	<i>IDE</i>	<i>KSB</i>	<i>KSEF</i>	<i>GR</i>	<i>MGE</i>
<i>IDE</i>	.744	.493	.069	.702				
<i>KSB</i>	.867	.630	.133	.263	.794			
<i>KSEF</i>	.866	.691	.164	.071	.365	.831		
<i>GR</i>	.905	.658	.230	.150	.276	.405	.811	
<i>MGE</i>	.828	.548	.230	.085	.350	.275	.480	.740

Table 4-3: Reliability and validity tests – in bold the square root of AVE

4.5.2.3 Common method bias

Our data was collected using the same measurement instrument, an online survey, so we had to control our model for common method bias (Podsakoff et al., 2003). We did a common bias test and compared our model with an unconstrained common latent factor (CLF) to another model with a CLF fully constrained to zero. A χ^2 difference test was found to be significant ($\chi^2 = 86, df = 19, p = .001$), indicating that we had shared variance among our constructs. Thus, we kept the CLF as an extra factor in our model to account for the common variance observed (Gaskin, 2017).

4.5.2.4 Measurement model invariance

We tested our measurement model invariance by imposing gross group constraints on our measurement model (Chen, 2007; Cheung & Rensvold, 2002). Methods based on χ^2 difference tests may be too sensitive to sample size and could reject good models with minor misspecifications (Bentler & Bonett, 1980).

First, we confirmed our model configural invariance as evidenced by the good model fit measured when estimating our two groups, Experts and Members, freely ($\chi^2/df = 1.579, CFI = .968, GFI = .923, AGFI = .895, SRMR = .0432$ and $RMSEA = .034$). Then we measured the difference between this constraint model and an equal loading constraint model. We applied recommended cut-off criteria for small

and unequal sample sizes (Chen, 2007): $\Delta CFI < .005$, $\Delta RMSEA < .01$, and $\Delta SRMR < .025$. Our model successfully passed the metric invariance test.

Finally, we tested scalar invariance with the following cut-off criteria: $\Delta CFI < .005$, $\Delta RMSEA < .01$, and $\Delta SRMR < .005$. However, our model did not achieve scalar invariance, and we had to remove constraints on KSEF and gain reputation (GR) constructs to pass successfully. Thus, we could achieve partial scalar invariance as presented in Table 4-4.

	χ^2	<i>df</i>	<i>CFI</i>	<i>SRMR</i>	<i>RMSEA</i>
Unconstraint model	442	280	.968	.0432	.034
Equal loading model	457.3	294	.968	.0433	.033
Equal intercepts model	483	303	.964	.0434	.034

Table 4-4: Comparison of model fit statistic for invariance test

This partial measurement invariance prevents us from comparing our results across groups for two of our constructs: knowledge self-efficacy and reputation gain.

4.5.3 SEM results

We tested our model by SEM, a robust statistical research technique for testing relationships between constructs with multiple measurement items (Joreskog & Sorbom, 1996). Our study relied on a widely accepted conceptual model that we wanted to test for multiple groups, and we then proceeded to construct effect comparisons, which are two of SEM's strengths (Lowry & Gaskin, 2014).

We introduced age as a control variable in our model after having confirmed that age group has a significant effect on KSB $F(4,505) = 2.382, p = .05$. Furthermore, emerging literature indicates that age influences knowledge sharing (Lazazzara & Za, 2016, 2019).

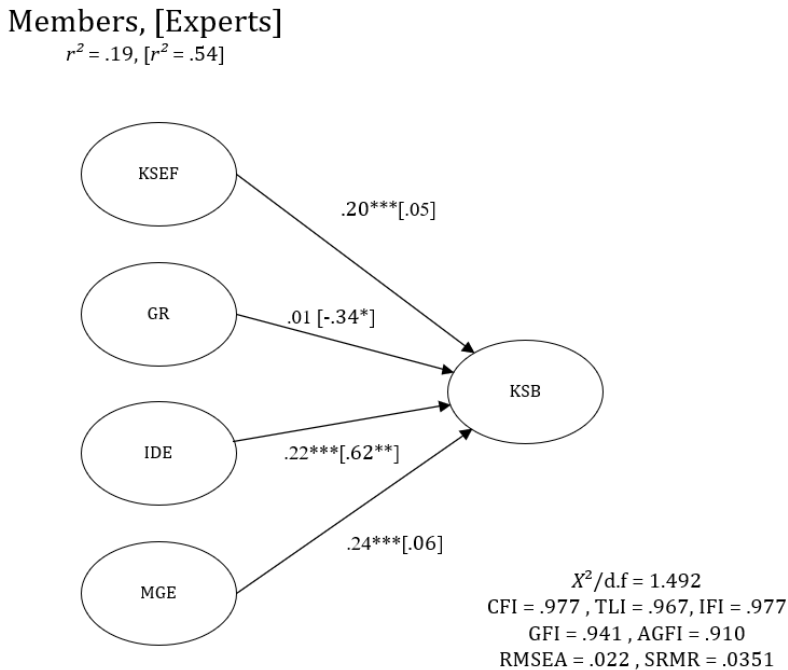


Figure 4-3: Results of the structural model, for Members [and Experts]

The explanatory power of our model for community members is evaluated by an r^2 value of .19. The model confirms the theory and hypothesis (H2b) about making

gain expectations (MGE). Members engage in knowledge sharing because they expect to make a financial gain or realize savings.

Hypothesis (H3b) on knowledge self-efficacy is also confirmed (KSEF) as theory predicts. Whether you are a member or an Expert, KSEF is a prerequisite to engaging in an online discussion (Bock et al., 2005).

Our model also confirms the hypothesis (H5b) that community members' adhesion to the community objective (i.e., promote sustainable living and ecology) correlates with their willingness to participate online to acquire novel knowledge on the topic actively.

However, the internalized extrinsic motivation to gaining reputation does not affect knowledge sharing. This is not a surprise; the Lowimpact website is not a social network, nor does it use ranking features for its contributors. On WKC's, social interactions are minimal, and actors are focused mainly on content (Nov, 2007).

Regarding the Experts model, the r^2 value is .54 accounting for more than half the dependent variable variance observed. Hypothesis (H4a) was refuted; GR is negatively correlated to knowledge sharing. Experts do not perceive their participation in the Lowimpact website as a marketing-related time investment. They probably do not consider this activity an additional channel to improve their online reputation and acquire novel customers.

We confirmed hypothesis (H5a), the identification with the collective goal (IDE) motivation is highly correlated with the dependent variable. By confirming H5a and H5b, we validate the relevance of a new internalized extrinsic motivator in online communities. Our results support previous evidence for similar adherence to the community's objectives. For instance, scholars have proposed ideology as a motivator in the case of Wikipedia (Nov, 2007) and the belief that software should be free in OSS development (David & Shapiro, 2008).

Hypothesis		Results	
		Experts	Members
H2.	Knowledge self-efficacy is positively related to knowledge-sharing behavior.	Not Sig	.20***
H3.	The material gain expectation is positively related to knowledge-sharing behavior.	Not Sig	.24***
H4.	Gaining reputation is positively related to knowledge-sharing behavior.	-.35*	Not Sig
H5.	A higher level of identification with the community's collective goal will positively affect knowledge-sharing behavior.	.61**	.22***
		$r^2=54$	$r^2=19$

Table 4-5: Results of the SEM²⁵

²⁵ * $p < .05$, ** $p < .01$, *** $p < .001$.

4.6 Discussion

The objective of this study was to examine if the motivations to share knowledge of various WBK community members were different. Thanks to a SEM, we have demonstrated that frequent and occasional contributors to WKC contributed for different reasons. This first finding is crucial to increasing active participation in online communities and therefore sustaining financial income and online visibility. A more detailed understanding of community members' motivations, combined with the dynamic perspective brought by SDT, allows us to make some recommendations.

Experts are mainly seasoned professionals; their participation in a WKC is not just another revenue stream or a marketing exercise to increase their online visibility. On the contrary, we have evidence that their participation is due to their adherence to the community object. Thus, our study does not find any positive effect of gaining a reputation to trigger knowledge contribution, which could be explained by the altruistic nature of free revealing of knowledge in WKC. Attracting and securing experts in communities is an ongoing effort. We encourage community managers to foster the underlying factors that support the internalization process, creating the conditions for Experts to feel autonomous and not over-moderated online. Furthermore, they should try to contact Experts directly to elaborate on their vision and ambitions for the community, with the objective of adding another dimension to the community in the experts' mind: It is more than merely a website to which they contribute; it is a group of individuals working toward the same objective.

WKC members' motivations are more balanced, driven by their interest in the collective goal linked to sustainable development and do-it-yourself practices. What is available online is a way to save money while reducing negative impacts on the planet. These finer-grained results have several implications for community managers, allowing more targeted actions for their constituencies. Knowledge self-efficacy stood out as an important factor that should be leveraged to improve activity

on a WKC. We invite community managers to put in place strategies to nourish this feeling and facilitate members' contributions, thus initiating a virtuous circle of participation that will, in turn, boost member KSEF and future contributions (Bock et al., 2005; Kankanhalli et al., 2005). Furthermore, this feeling of competence is a major supporting factor in internalizing extrinsic motivations that we identified as significant in contributing to knowledge sharing (Legault, 2017).

Our second finding is the strong relevance of a construct from the SDT theory strain of literature that complements the commonly agreed-upon list of motivators (Von Krogh et al., 2012, p. 654). Identification with the collective goal (IDE) stood out as a strong motivator for both types of community members. Identification with the collective objective is not solely a “crucial factor influencing the individuals’ behavior” (Spaeth & Niederhöfer, 2020) but also a significant motivator to knowledge-sharing within WKCs. Our results confirm that adhering to a collective objective is a significant motivator for sharing knowledge (Leonard et al., 1999). This construct contributes to closing the gap between the two views on knowledge-sharing activity in communities. On the one hand, individuals' motivations to participate in a collective effort can be viewed as a somewhat transactional process subject to cost-benefit (Lerner & Tirole, 2002) or own-use value assessment (Roberts et al., 2006). On the other hand, research on open communities has highlighted that motivations are highly context-dependent – to the organizational model or community topic (Hausberg & Spaeth, 2020) – and that active community participation can be considered a social practice (Von Krogh et al., 2012).

4.6.1 Limitations and suggestions for future research

It has been a challenge to design a single survey that Experts and Members could understand in the same way. Knowledge sharing can happen both on the platform and in real life, confusing our respondents and potentially diluting our constructs' size effect. We consider that our model demonstrates a good fit with the data

collected via our surveys. However, we have been conservative with our conclusions, given the variance we observed.

Our research design is based on a multigroup comparison. This turned out to be a constraint when evaluating the goodness of fit of a common model for what ended up being two quite differently motivated groups of people. Hence, we obtained partial measurement invariance that led us to proceed to a complementary analysis. We hope further research will succeed in conducting a multigroup comparison with complete measurement invariance, allowing a direct comparison of all effects.

We obtained a response rate of more than 60% for experts. However, the relatively limited number of respondents prevented us from having statistical significance in the effect of various constructs. We invite researchers to continue our work with a larger population to develop a more comprehensive view of the effects at stake.

Our study also opens up avenues for further research. Involvement in a community is a dynamic process where long-term participation results from a progressive alignment between individual values and the community objective. Further studies are needed to clarify how this process is different from identification with community members (Rafaeli & Ariel, 2008). It has been shown that after a long period of participation in a community, members self-identify with the group, and participation becomes a goal in itself (Shah, 2006).

With this paper, we have started to unveil how SDT can help us understand why community members remain involved in communities over a long period. The process of internalizing extrinsic motivations takes time but is a powerful factor over the long run. Indeed, scholars argue that long-term involvement within a community becomes “intertwined with their lives, creating the perception of a moral obligation associated with the pursuit of the unity of life” (von Krogh et al., 2012). Hence, we invite researchers to explore how SDT helps explain the dynamic mechanisms at play in knowledge-sharing motivations within the community over an extended period of several years.

5. How commons support innovative project development: Deep dive into the world of innovation commons²⁶

5.1 Introduction

According to traditional research into innovation, primarily influenced by Schumpeter's work (1934), the process that gives birth to innovations starts in a corporation or at a university (Edquist & Hommen, 1999) where users are viewed as passive stakeholders. For more than thirty years, this model has been increasingly proven wrong in the field of digital technology. Community-based and user-centered innovation models have thrived (Benkler & Nissenbaum, 2006; Hippel, 2005), demonstrating that these emerging actors are central to innovation. These individuals collectively form movements that are often powered by ad-hoc institutional arrangements and governed as commons. For instance, this model became mainstream in high-performing software development, with 100% of the top 500 super calculators relying on open source operating systems²⁷, making the OSS movement key to various multi-billion dollar industries (Yin et al., 2022).

Recently, a new type of open movement thrived, supported by the affordability of new decentralized means of production such as 3D printing or programmable hardware: OSH. It tends to replicate the successful OSS model but with hardware devices. However, the tangible nature of hardware devices makes the management of OSH communities more challenging. Resources shared within the community are subject to subtractability, expertise is scarce (Lerner & Tirole, 2002), and the size of the community is limited by the obligation to meet and collaborate at dedicated premises. Legal tools which proved to be instrumental to protect OSS products are not as effective to protect artifacts built by communities (Ackermann, 2009).

²⁶ The chapter has been sent to an international journal for publication and is under review

²⁷ <https://www.top500.org/statistics/list/>

Finally, the collectively built device may be subject to specific industry regulations (Carpentier, 2021). For instance, during the first months of the COVID-19 pandemic, hundreds of OSH projects emerged with the ambition to save lives and to make a real impact. Although the definition of success in OSH is quite broad, the success rate of these endeavors has been meager with very few complex projects reaching the bedside (Antoniou et al., 2022). OSH is still un very young area of innovation, full of promises in terms of lowering project costs, improving resilience of equipment and empowering end-users (Gibb & Abadie, 2014; Gibney, 2016; Pearce, 2015b). But the regulatory framework and legal protections are incomplete and inadequate. These conditions hinder entrepreneurs' ability to establish viable business models in a potentially too risky environment.

In the context of emerging technologies, scholars have identified a new type of commons that proved to be cost-effective in assessing a project's feasibility and potential market opportunities for innovations (Allen & Potts, 2015). IC help communities identify the conditions for successful and sustainable project implementation (Allen & Potts, 2016). Flexible institutional arrangements, such as an extensive portfolio of commons, ranging from the KC (Ostrom & Hess, 2007) to the digital commons (Dulong de Rosnay & Stalder, 2020), have been shown to be instrumental in improving the success of open communities (Broca & Coriat, 2015). However, our understanding of how commons in general, and IC in particular, support OSH projects is relatively limited. Longitudinal case studies on commons are rare; existing cases usually focus on a project's early stages or when it is completed. Here we answer the call from Frischmann et al. (2014) to explore this institutional arrangement over time.

Thus, we followed an innovative project from inception to market launch. We shed light on various kinds of commons supporting the community's transformation during the execution of the project and how these transformations were instrumental in the project's success. We articulated RQ3: *How do commons evolve to support the development of innovative projects?*

Our paper reveals that community-led projects may require different types of commons according to the specific development stages. A unique commons, despite flexible governance, may not be suitable to support a project throughout its lifetime. Instead, various commons deal with different shared resources and coexist within the same project and at the same time. Some commons also evolve or disappear from one project phase to another. While in other projects, commons are established very early in the ideation phase and remain active after the end of the project. Based on our longitudinal case study, we propose a process theory to explain the temporal order and sequence in which these commons formed and disappeared during project development.

This paper is organized as follows. First, we introduce the various forms of commons relevant to the understanding of this manuscript and describe the OSH movement and why this notion is being challenged and broadened by scholars to account for the sort of product developed and the openness of the production process. Then, using a process research methodology, we explain the sequence of events and the implications for the supporting commons during the nine years of project development. Finally, we discuss how our empirical findings enrich the IC literature and underline the relevance of ICs in setting up start-ups or hybrid institutional models that seek to stimulate and scale up innovative projects.

5.2 Literature review

5.2.1 In the jungle of the commons

In 2008, Elinor Ostrom won the Nobel prize. She shone the spotlight on the commons, a form of self-organized institutional arrangement put in place by communities to manage shared resources and subject to a social dilemma. For centuries, the commons has helped to address natural resource management issues such as overconsumption, congestion, pollution, or maintenance for the benefit of all. However, the notion of commons is still a challenge to explain as it covers various realities; a shared resource (Hess, 2012), a form of governance (Dedeurwaerdere et al., 2014; Madison et al., 2010) or a social production (Hardt & Negri, 2009; Öztürk et al., 2014).

In the famous article ‘The tragedy of the commons’, Garrett Hardin (1968) describes how the absence of governance of a shared resource can lead to the destruction of the resource itself. Typical examples of successful usage of commons are fisheries (Berkes et al., 1989), grazing systems, forests (Gibson et al., 2000), wildlife, water resource, and agriculture. Appropriate governance plays a crucial role in ensuring long-term sustainability and proper functioning of the commons to “achieve compatibility between interests of the different actors who participate in the commons, working on the assumption that these interests do not necessarily coincide” (Ostrom, 1990).

In the mid-1990s, scholars realized that commons might be interesting institutional arrangements for dealing with challenges posed by the expansion of the internet. Hence, the second generation of commons emerged in the area of information, science (David, 2001), software (English & Schweik, 2007; Schweik, 2014), intellectual property (Boyle, 2008), sharing economy (Benkler, 2006), genetic information, and research (Contreras, 2014). Knowledge has been progressively understood as a resource that must be protected and managed as CPR (Hess & Ostrom, 2003) as it may be at risk of enclosure, pollution, and lack of maintenance

(Frischmann et al., 2014; Ostrom & Hess, 2007). This broad family of KC is growing fast and is increasingly applicable to various intangible resources.

However, analyzing KC is more complex than analyzing TC. A KC organizes the production of the shared resource, manages its consumption, and protects it. Moreover, it is sometimes challenging to identify what is actually produced within a KC (Madison et al., 2010).

Emerging literature has recently stated that commons might not be exclusively composed of either tangible or intangible resources, and in our case study we exemplify how KC can be hybridized (Basu et al., 2017; Potts, 2019). Thus in the article, we will use the Basu et al.'s (2017) definition of HC: “composed of both a physical component (the tangible one [...]) and an informational component (an intangible one[...])”.

For instance, the resources shared in common in OSH projects are the expertise and know-how to build an artifact. But hardware is also needed for the project, such as electronic components and tools pooled in a specific location. These shared resources must be managed as CPR and are subject to typical tangible resource social dilemmas, such as congestion or scarcity.

A third generation of commons: The innovation commons

At the beginning of an innovative project based on disruptive technology, the level of uncertainty is high. Usually, a group of people from various fields of expertise gathers to assess the feasibility and opportunities for building something collectively. They exchange information on potential technology, market structure, regulatory constraints, potential funding, and relevant partners to help them achieve their objective (Allen & Potts, 2016). As Nobel prize winner Friedrich Hayek (1945) puts it when describing the inception of innovations, “knowledge [...] never exists in concentrated or integrated form but solely as the dispersed bits of incomplete and frequently contradictory knowledge which all the separate individuals possess.”

These pioneers can form an IC that “peer produces information to enable entrepreneurs, who are among the peers, to act individually and cooperatively to

reduce uncertainty and reveal the outlines of an opportunity” (Potts, 2019, p. 16). Here, the shared resource is not the technology per se, but insights from the market, needs, and information on the potential technological solutions that could facilitate the development. Allen and Potts (2016) argue that these commons represent “a *third generation* of commons, a higher order form of information and knowledge *about* information and knowledge.”

The IC combines institutional mechanisms aiming to ease the process of entrepreneurial discovery (Hausmann & Rodrik, 2003), facilitating the transformation of ideas into innovations. It facilitates uncertainty reduction about the project so that actors can actively start to implement it with a reasonable degree of confidence. The IC also helps identify the best institutional arrangement for further project development.

Moreover, ICs are efficient organizational arrangements for organizing and coordinating knowledge sharing. They are cheaper than private or public institutions from the point of view of transactional costs. They pool various types of shared resources, including physical resources, access to people, ideas, or experiments. For instance, hackerspaces are small social organizations where these IC can emerge; individuals meet, work together, and learn from each other (Kostakis et al., 2015). Potts (2019) posited that ICs are composed of two commons: a “Commons of material and technological innovation inputs and resources” (CMTIR) and a second “Commons of entrepreneurial information” (CEI). The latter is the more valuable, but an active contribution to the former is mandatory to gain access to it. Ultimately, ICs are temporary and disband once the uncertainty around the object of study is reduced and when a targeted institutional model is identified.

5.2.2 From Open Source Hardware to open source product development

OSH is a recent phenomenon supported by the availability and accessibility of various technologies such as 3D printing; thus, significant projects emerged in the

past decade. The Open Source Hardware Association’s official definition²⁸: OSH refers to “tangible artifacts—machines, devices, or other physical things—whose design has been released to the public in such a way that anyone can make, modify, distribute, and use those things.” This definition stresses the parallels between this practice and the ethos of the open source movement that was particularly successful in OSS development (OSSD) (Gacek & Arief, 2004).

However, emerging literature claims that this OSH definition is too ambiguous because it focuses solely on the product itself (Bonvoisin et al., 2021). Scholars argue that the process of building the artifact could equally be open or closed, bringing a new dimension to the official definition. They prefer the term open source product development (OSPD) (Balka, 2011; Bonvoisin, Thomas, et al., 2017), which captures the openness of both the project and the product (Table 5-1). Thus, we will allude to OSH *projects* or the OSPD interchangeably when considering this additional dimension of process openness.

		Process openness		
		Regardless of any process	Closed process	Open process
Product openness	Closed product	Proprietary hardware	Closed Innovation	Private open Innovation (e.g. crowdsourcing, social product development)
	Open product	Open source hardware	Public Innovation	Open source product development

Table 5-1: OSPD dimensions of openness, adapted from (Bonvoisin et al., 2021)

OSPD relies on communities to support their development; they establish commons in a similar way to OSS communities (Schweik & English, 2012). These commons support a “decentralized and collaborative model of value creation” where “people

²⁸ <https://www.oshwa.org/definition/>

jointly develop and freely share designs” (Moritz et al., 2018). They are fragile, subject to social dilemmas, and can die if not actively maintained or if collective activities stop (Balka et al., 2010). Nevertheless, OSH projects have already been shown to build value for the scientific community, saving funds in research and leading to innovative business models (Pearce 2017; Li et al. 2017).

Finally, the very nature of the physical artifact produced generates additional challenges affecting the community. For instance, the necessary expertise can become very narrow and challenging to find. It also requires dedicated infrastructure such as premises where members can meet and work on prototypes, hardware components, or tools (Bonvoisin, Mies, et al., 2017).

5.3 Methodology

5.3.1 Research approach

We adopted a process research methodology to uncover the underlying mechanisms explaining why commons evolve and why they evolve in this way (Van de Ven & Huber, 1990). We propose a “process theory” to explain “the temporal order and sequence in which a discrete set of events occurred based on a story or historical narrative”(Van de Ven & Poole, 2002).

Thus, this article is based on three years of direct observation (from 2019 to 2022) of an OSH community and six years of historical data analysis (from 2013 to 2019). Our objective is to identify key decisions taken by the community and external events at each stage of project development, the rationale for these decisions, and the consequences for the supporting commons.

The nature of our research objective and the type of data to be obtained led us to a qualitative approach. This allowed us to gain a rich understanding of what happened during the development of this long project (Holstein & Gubrium, 2004) and the consequences for the commons used to support this initiative.

Furthermore, we relied on a temporal bracketing strategy to frame our historical data. “The decomposition of data into successive adjacent periods enables the explicit examination of how actions of one period lead to changes in the context that will affect action in subsequent periods” (Langley, 1999). We studied a project development pipeline and aligned our temporal bracketing with regular project management stages (Figure 5-1) (Cooper, 2015). Thus, we could describe major events and governance decisions for each project phase and identify how they influenced their supporting commons and subsequent project phases. We particularly focused on preconditions to starting the next stage and described the type of *discontinuity* at the frontier of two phases, making them mutually exclusive (Langley & Truax, 1994).

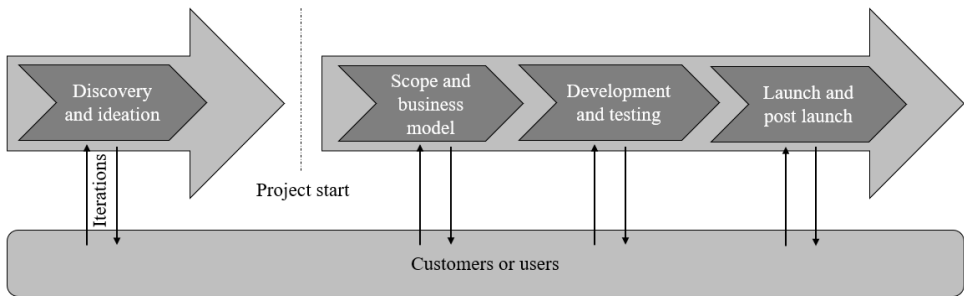


Figure 5-1: Adaptation of the stage-gate Xpress model (Cooper, 2015)

In this case study, potential future users are continuously involved, as recommended in the project agility manifesto²⁹. This constitutes a significant evolution in the project management paradigm, illustrated by the evolution of the stage gate model (Cooper, 2015).

²⁹ <https://agilemanifesto.org/>

5.3.2 Case selection

The range of projects that OSH communities are tackling is vast, ranging from prosthetic hands³⁰ to open source MRI imaging (Winter et al., 2019) and open electronic platforms and sensors³¹ – the directory of the Open Source Hardware Association lists hundreds of such projects³². However, only a fraction of them are likely to ever significantly impact our daily lives. We selected a project with a substantial innovation component that is close to delivering a product to market, to allow us to witness the emergence of an IC.

Description of the project

The community describes its work as “an open and collaborative project bringing together an international community of multidisciplinary experts and professionals around a common goal, to make medical imaging accessible everywhere in the world.” They promote an innovative medical practice in clinical examination called echo-stethoscopy (Elezi, 2018). This practice requires a modernized version of a stethoscope composed of an ultrasound probe and a smartphone which provides sound and images of the patient's internal organs during a clinical examination (Narula et al., 2018).

Their ambition is to make this practice widespread worldwide, including in low and middle-income settings, rural zones, and emergency wards. Affordability is a key to reaching a critical mass and making the practice a new standard. Similar devices currently exist on the market, but their cost prevents them from being widely distributed, hindering the scientific community's ability to develop a specific semiology for the usage of this tool. Therefore, the community decided to rely on an open source design-to-cost approach to building this missing equipment.

³⁰ <https://enablingthefuture.org/>

³¹ <https://www.arduino.cc/>

³² <https://certification.oshwa.org/list.html>

5.3.3 Data collection

We conducted twenty-seven semi-structured interviews with various community members, which lasted between 30 and 90 minutes for an average of 60 minutes and accounted for 299 pages of transcript. We interviewed the founding members of the commons, various software and hardware developers, volunteers, medical doctors, and medical staff to obtain a reliable picture of these commons both internally and externally. Furthermore, to continuously check the validity of our findings, we conducted quarterly follow-up interviews and targeted conversations from 2020 to 2022. These regular contacts helped us to refine our understanding of specific topics: medical device regulation, intellectual property, and commercialization. To facilitate informants' understanding of our questions, we provided a glossary with definitions of key terms. Moreover, the semi-structured interview format allowed for informants to ask questions or clarifications. Our questions were then updated to include further details about emerging findings, connecting the conceptual level to the managerial level.

We also attended team meetings and collected archival documents such as bylaws, activity reports, and communication material for a period covering almost a decade to triangulate and validate our data (Yin, 2014). Data collection took place over 30 months and covered nine years of project development.

5.4 Findings

5.4.1 Time bracketing and project structure

Our time bracketing strategy led us to structure our empirical findings by project stage. The first stage, called “Discovery and ideation,” started when several actors met to acknowledge the medical need and discuss whether the challenge could be solved by an innovation (Q4 2013). This phase ended with the first demonstration of a functional proof of concept (Q4 2015).

The second project stage, “Scope and Business model definition,” began when uncertainty about the project's feasibility was sufficiently reduced by the information gathered during the first stage. The project was considered achievable with the open technologies available, and medical experts confirmed the relevance of the innovation. The main activities allowed the community to scope their project clearly and elaborate a sustainable business model. This phase ended when funds to initiate the development of the product were secured. A business model and the supporting organization were identified. Product specifications were progressively established in preparation for the manufacturing phase.

The third project stage, “development and test” started with developing the medical device within a quality management framework as per regulatory recommendations. The devices produced were trialed on patients during clinical tests to validate that they are safe and functional. This stage ended with the awarding of CE marking that confirms the device can be sold and used on patients.

The final project stage, “launch and post-launch,” started with the commercialization of the probe and ends when the existing equipment is superseded by a new version.

For each project stage, we organize our findings around the relationship between the main events of the stage and the supporting commons. We also pay particular attention to key events that allow the next stage to start and structure our findings in the project process flow-chart (Figure 5-2) to illustrate “the temporal order and sequence in which a discrete set of events occurred”(Van de Ven & Poole, 2002).

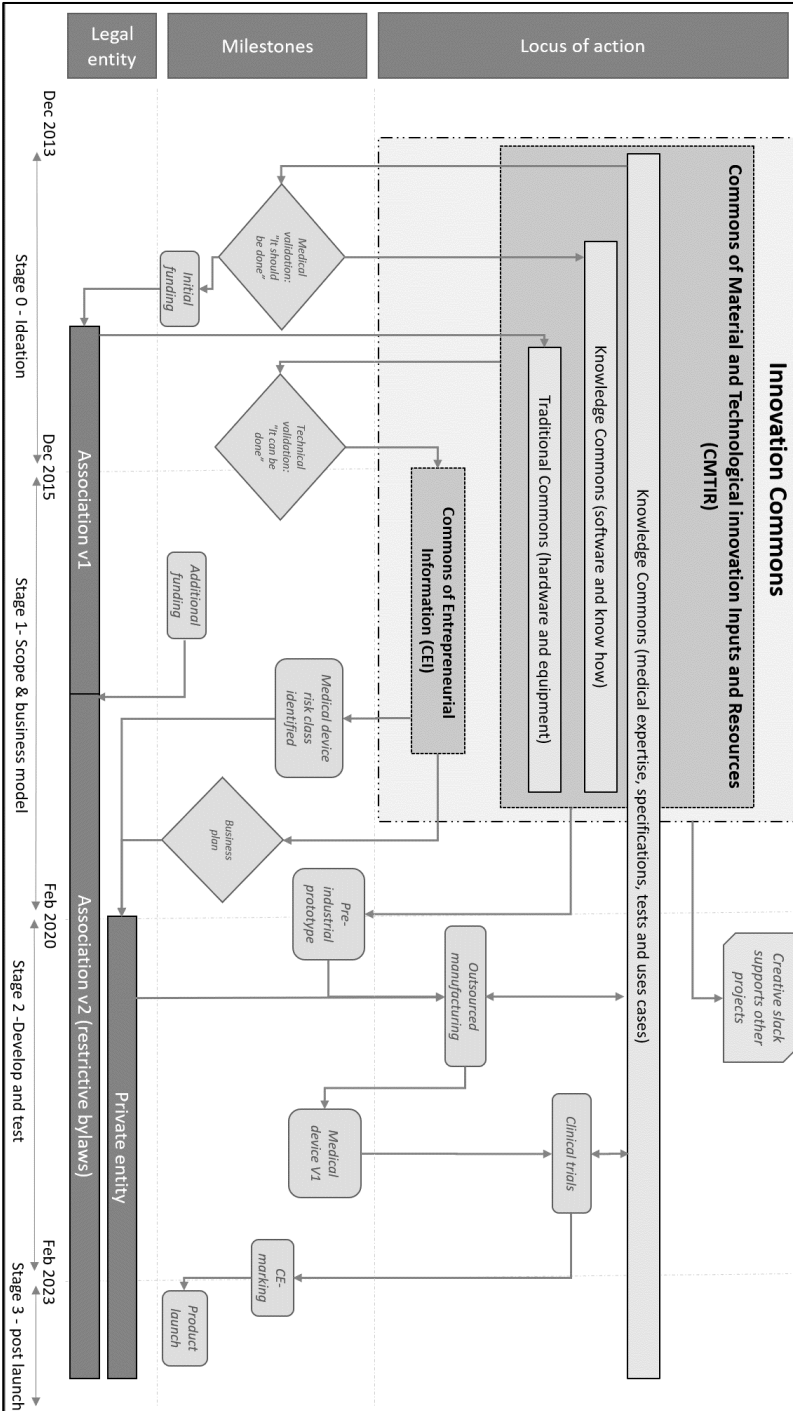


Figure 5-2: Project process flow-chart

5.4.2 Discovery and ideation stage

Our case starts with the inception of an innovative and complex OSPD. The production of a medical device is heavily regulated. Moreover, in 2013, the OSH movement was still relatively new, mainly composed of 3D printing-related projects or seminal hardware building blocks like the Arduino project, which is on the verge of becoming a game changer for the movement (Gibb & Abadie, 2014).

The first stage of innovative product development (Cooper, 2015) is often considered stage zero – since the project has not yet started. Only at the end of this phase is a decision made to establish a clear business plan, if an opportunity arises. The actors' objective during this phase is to assess whether an “intuition” can be sustainably realized with a product or a service. A founding member describes the project rationale:

A proportion of the world's population does not have access to diagnostic imaging. There is the possibility of forging the stethoscope of the twenty-first century. Clinical examination has not evolved for a century and a half, since the invention of the stethoscope by Laennec. We conduct clinical examination, called semeiology, using tools that are not very sensitive, not very specific, rudimentary. There must be devices that make it possible to enrich the clinical signs collected by practitioners in this initial exchange with the patient.

For the project under study, this stage was characterized by the encounter between two medical doctors facing a medical challenge and an engineer interested in “open movements.” They had a disruptive idea and wanted to check two things straight away before heavily investing time and money into their idea. The founders pooled distributed information by consulting and onboarding various talents and expertise to reduce uncertainty before proceeding with the project. A founder declares:

There are about thirty or forty of us, I gather many experts: acousticians, physicists, medical doctors, engineers around the question: “Is there a technological path which makes it possible to develop this [ultrasound] probe within the price range we want”. [...] And at the end of the meeting, it appears that yes, there is.

With this series of meetings they validated with their medical and technical peers whether their idea made sense.

We confirmed the medical rationale. There was this software language I was a bit proficient in, [others] had past experience with hardware. Then I said to myself: well, it makes sense to look a little bit further.

In sum, they were able to justify building a cheap successor to the stethoscope that would improve medical examinations.

Their second step was to validate whether building a cheap and open medical device was possible before committing more time and energy to this nascent project. However, they lacked the necessary expertise and had to source external help. As a founding member stated:

We knew nothing, none of us knew anything about hardware. We didn't even talk about Open Hardware, but hardware. We didn't know what a Raspberry Pi or an Arduino was. Well, we didn't know!

They quickly realized that various actors were interested in developing this innovative solution: think tanks³³, start-ups, crowdsourcing platforms, training organizations³⁴, medical institutions, caregivers, and volunteers from other open source projects³⁵. Hence, they adopted an “open movement” approach to filling that

³³ [https://plus.wikimonde.com/wiki/Club_JADE_\(Think_Tank\)](https://plus.wikimonde.com/wiki/Club_JADE_(Think_Tank))

³⁴ <https://www.aforp.fr/>

³⁵ <https://medium.com/epidemium>

knowledge gap and promoted collaborative product development. The extended group assessed the feasibility of an affordable medical device. They used to meet in fab labs³⁶ and hackerspaces as they had no premises to organize a series of brainstorming and public events. These activities generated knowledge that has been pooled in a particular commons: an IC.

5.4.2.1 The emergence of an innovation commons

During the ideation stage, we witnessed the emergence of an IC as described by Allen and Potts (2016): “an innovation commons is predicted to emerge along an innovation trajectory, within an economy, where uncertainty is highest about the pathways through which to develop a new idea or technology.”

Even before the beginning of the project, actors from different horizons aggregated the latent information distributed among various individuals to assess the relevance and feasibility of their idea.

In 2013, the commons and open movements were very “trendy.” Many ‘fab labs’ emerged in Paris, the successes of the open source movement inspiring OSH communities (Ackermann, 2009; Hansen & Howard, 2013). A founder confirms:

It was 2013, and there was a very active scene in France around open data, open source, in particular, a media called OWNI³⁷[...]. I think it crystallized a whole generation around the idea that we can do things differently; there are alternative models. [...] The emergence of the notion of commons [...] to build or co-build a society, escape from consumption at all costs, reclaim the means of production.

The ability and speed with which the community could gather expertise from various fields was the result of many parallel initiatives with similar mindsets that

³⁶ <https://lapaillasse.org/>

³⁷ <https://fr.wikipedia.org/wiki/OWNI>

came to fruition in Paris at this period of time, famously described as Hayek's "knowledge of time and place."

The ICs would have never emerged unless similarly minded initiatives had been available in the city at that time. Furthermore, the very nature of open projects is to regularly fork – developers take a copy of a project source code and create a novel software- (Nyman & Mikkonen, 2011), accelerating dissemination of ideas and concepts across various open communities.

5.4.2.2 Unfolding the innovation commons

Potts (2019) posited that ICs are composed of two commons: a CEI and a CMTIR that "pools physical and technical resources, including kit and knowledge of the sort that engineers value."

At the beginning of the ideation stage, the CMTIR was mainly composed of knowledge distributed among members. With their understanding of the clinical challenges, medical doctors agreed that this idea was medically relevant. They agreed that "the project should be done."

Hackers and enthusiasts with the necessary understanding of the technology soon joined them. They had to assess the feasibility of building a medical device with an off-the-shelf hardware component.

However, OSPDs require more funds than purely digital projects, and they must finance tools, electronic components, equipment, or premises upfront before their commons come into existence.

Interested by the community's vision and the solid background and network of the founders, a philanthropic foundation supported their feasibility assessment exercise. In turn, this led to establishing a legal entity in Q1 2015, a NFP organization able to receive and manage the funds. Finally, this legal entity also allowed Assistance Publique – Hôpitaux de Paris (AP-HP) to make premises available to the newly formed association.

This commons is unusual, as part of the pooled resources are intangible (knowledge, software code, experience sharing), typical of a KC, while the rest are tangible (components etc.) The digital part of the common is very similar to a classical OSS project. They rely on a common source repository: GitHub. Participants contribute from a distance and push their code to the shared repository that is arbitrated and merged by an administrator.

On the other hand, tangible resources are subject to excludability and subtractability: hardware resources, prototypes, and space in the lab to work on the device. For instance, only one prototype was available for a very long period; it could not be shared with multiple developers at the same time. Furthermore, anyone who wants to work on the prototype has to come to the association's premises and check the availability of the prototype in advance. Hardware is a costly resource and has to be governed accordingly. This limits the number of possible iterations to identify and align on the best technical design before implementation. This part of the commons is governed as CPR to control access to physical resources and hardware that is subject to congestion (Kostakis et al., 2015).

In summary, the CMTIR pools' intangible and tangible resources are governed in parallel in this commons. This leads us to consider this part of the IC an HC (Basu et al., 2017).

After several months of work, the technical members of the community were able to validate the technical feasibility of the project. This gave the second green light to the project: "It can be done!"

With both medical and technical validation, the group of founders were able to seriously consider further developing their vision. They started to pool knowledge that would be helpful in setting up a sustainable organization in the CEI. Initially, they had no idea what the best legal vehicle to support their project would be. They pooled information on regulatory constraints, potential business models, and potential public and private funders. As posited in theory, this commons was only accessible to members of the CMTIR that had already shared information and effort.

5.4.2.3 The end of the ideation stage

In September 2015, the official presentation of an “acoustic bench” proved that ultrasound could be emitted and received by a completely open-designed device. A couple of months later, a refined proof of concept (Figure 5-3) was presented to a broad audience of experts and potential donors. They concluded that the project was viable and agreed to support it.

These two presentations mark the end of the ideation phase. The project entered the scoping stage with the clear ambition of building a device and making it available to medical doctors worldwide.

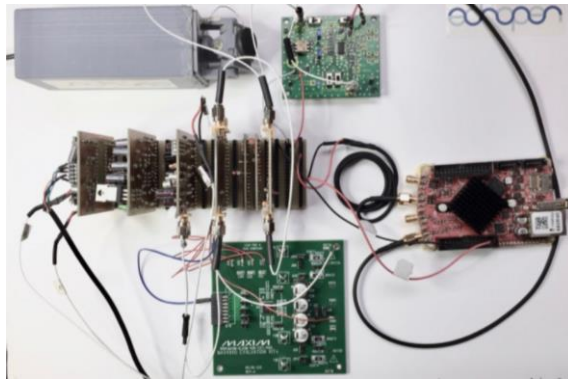


Figure 5-3: Initial proof of concept

5.4.3 Scope and business model definition stage

The ideation stage allowed a core group of stakeholders to validate the relevance of their idea and assess the project's feasibility. As their idea for a medical product took shape, they slowly became entrepreneurs with the strategic intent of significantly impacting global health. Hence developing an affordable medical device became a mandatory step to reaching patients worldwide and creating a novel medical practice. A founder explains the shift from the ideation to the project stage, which

was driven by technical considerations and a greater orientation toward delivery in subsequent steps:

I think it's good to say [that we are] not only going to open up the technology to make it accessible, but also to set up elementary bricks, and that others will be able to pull together themselves". We must keep the idea in mind that it's a question of health, [...] and that technology will be used, it will actually be used on patients!

The objective of the project's second stage was to develop a solid business plan and grow the technical and medical communities to design a pre-industrial prototype. The medical community had to describe the conditions under which the device would be relevant and safe. The technical community had to produce a fully functional pre-industrial prototype for use by an industrial partner as a model for the final product.

5.4.3.1 A story of institutional evolution and regulation

The business model and scoping phase is an intense stage in which legal vehicles evolve to support the project.

The association

The community secured several sources of funds over the years and has been able to produce a functioning prototype of a medical device. At one point, the open governance of the supporting association was deemed inadequate; in effect, anyone who paid a low membership fee could obtain a right to vote at the annual board. This opened the door to a potential coordinated and hostile takeover of the commons and its fruits, a potential enclosure. Thus, in September 2018, the bylaws were revised to prevent anyone from acquiring a right to vote at the annual board unless duly validated by existing community members.

A second significant modification in the governance of the commons happened during this project phase in order to comply with medical device regulations. The community built a probe to capture the patient's medical parameters and smartphone software to display the information captured. Depending on the nature and purpose of a medical device, the effort required to comply with medical regulations may significantly impact the product development process.

It is critical for a community to understand the requirements needed to obtain regulatory authorizations during the scope and design phase, e.g., EMA in Europe, FDA in the US. The class of risk for a medical device depends on an official classification³⁸. For instance, if the device's purpose is only for information, it is considered class I. An invasive or active device is considered to be class II, and devices with the highest level of risk such as implants or stents are considered class III. The higher the risk class, the more stringent the quality process, ranging from self-assessment for risk class I to a notified body inspecting and controlling the medical device manufacturing process for risk classes II and III. Most medical OSPDs have a low-risk classification, for instance, 3D printed objects, even prosthetic hands. Nevertheless, an echo-stethoscope that emits ultrasound is considered to be class IIa³⁹ (a non-invasive medical device) with potential risks for the patient comparable to intensive care monitoring equipment.

The manufacturer – the legal entity building the device – must follow a specific conformity assessment before placing a product on the market (Twomey, 2013). A notified body will then have to control and inspect the device, its documentation, and the building process before commercialization.

An informal organization can hardly fulfill this regulatory inspection, where procedures are vague or non-existent. In the absence of a quality management system, volunteers cannot be held accountable (Carpentier, 2021). Creating a private

³⁸ Medical Device Directives (MDD): MDD 93/42/EEC; MDR 2017/745; AIMDD 90/385/EEC

³⁹ Regulation (EU) 2017/745 of the European Parliament and of the Council of 5 April 2017 on medical devices.

legal entity to conform with these requirements became necessary. Thus, in February 2020, the need for compliance with the regulatory framework pushed the community to split its activities between private and NFP entities.

The private entity was to be in charge of the medical device manufacture, in compliance with applicable regulations ISO 13485 for the smartphone app (Abuhav, 2018) and CE mark for the probe, and commercialization. It would also search for venture capitalists and private investors.

The NFP organization was to focus on knowledge dissemination, training, and long-term innovation with academic partners for a new generation of probes. Moreover, the private entity was to finance the non-for-profit organization to sustain the commons, which would continue to pursue the initial vision of disseminating knowledge and novel medical practice. A founder elaborates how the NFP would be specialized:

The association's activities in the future will be more focused on open R&D with communities to create fairly generic tools, whether [...] it's components, software tools or whatever. And to work on the distribution in the countries of the South or [...] to support the distribution of clinical ultrasonography in the countries of the South to make these technologies accessible.

This governance shift was a sign that the IC was no longer needed for this project level. Uncertainty had now been drastically reduced, and there was a more precise way forward for the project. The collaborative technical work would be passed over to an industrial partner under the form of a pre-industrialized prototype. The industrial manufacturer would be in charge of developing and delivering a fully compliant solution, including the CE-marking.

At the end of that stage, the last active commons at the project level was the medical commons that pooled and enriched medical knowledge on training, semiology,

medical targets, use-cases in the global-south, and social factors for using the device. A community member exemplifies:

In Benin, we work with a [partner school], on the training course for midwives. The idea is to offer training adapted to the context and profile of future users, identify access issues; with Internet connections, access to hardware.

From an OSPD standpoint (Table 5-1), the project moved from purely open source product development to a closed product supported by a community closer to classical open innovation project (Chesbrough, 2003).

5.4.3.2 The end of the innovation commons

ICs are temporary by nature and “disappear” when the uncertainty about the path for developing an innovation becomes clearer. Nevertheless, even though the IC disappeared at the project level, it left valuable resources for further work. Thus, community members' experience, documentation and project lessons-learned accumulated as latent knowledge or “creative slack” (Cohendet & Simon, 2007). This notion refers to the notion of organizational slack proposed by Penrose (1959), highlighting how organizations have a stock of unused or underused resources at the end of a project (e.g. knowledge, assets, skills and expertise). This organizational slack is a formidable reservoir of past experiences, lessons learnt and best practices available to improve future innovation projects.

In detail for this case study, the IC's two subcomponents delivered two different kinds of valuable resources. The CEI developed into a business plan at the end of the scope and business plan stage. Entrepreneurial-related information was compiled to answer the following question: How do you build a sustainable business model to manufacture an affordable product while promoting an open approach? A corollary to this question is: What would be the best institutional arrangement to support this collective effort?

The CMTIR transformed into a KC accessible to other OSH projects in the form of various documents and digital repositories (e.g., GitHub, Slack, websites, scientific articles). Together with the IC tacit knowledge they contributed to the creative slack of the association available for other endeavors. We have evidence that other projects reused a substantial part of the work produced for other purposes, but this is out of the scope of this study.

5.4.3.3 A medical knowledge commons

We have developed a medical device with doctors for doctors. [...] And that is also why it makes sense for it to be installed directly in a hospital. Because we worked with the radiography service and they came every week, [sometimes] twice a week. All department heads, sonographers, radiologists, interns, doctoral students, you name it, it was a continuous flow, and that is critical. -A community member.

During the scope and business model project stage, the medical community gave cost-free expertise to help design the probe in terms of defining appropriate image definition and its form factor, as well as advising on the app functionality, user interface, and ease of use. A medical doctor explains the dynamics around the form of the probe:

Students came up with several probe designs and [...] they were proposed to doctors who assessed them: “Well, yes, too small, that size would not work” or “It is a little bit large since it has to fit in a pocket.”

The medical community contributed to keeping the overall price of the device down and made key contributions to the specification, a developer explains:

The challenging part of the project is that we are the builders, but we are not the users, it is very different [from developing] for Linux.

Moreover, the medical community defines the services and semiology linked to each potential symptom detected.

Target identification

This medical community had a role in defining the field of application of the echostethoscope, basically determining in which cases the device could be helpful and how to interpret the results displayed on the screen. Organs are considered targets, and the community is interested in identifying the visible signs of a potential pathology. A public health doctor explains the collective process that led to a list of potential targets:

I had, therefore, reviewed the literature, identified several contexts. ...we had brought [...] fifteen doctors from the community and presented them with several results.... Then we asked them [...] what kind of situation, level of competence would be needed [...]. We ended up with a list of targets: [...] ninety medium-term and about twenty very short-term, on which we are going to have to train people and for which we seem to have the best validation protocols for the use of echostethoscopy.

Meta applications	Organs	Applications	Action	Object
Abdominal	Abdominal aorta	Aneurysm screening	Screening	Aneurysm
Thorax adult & pediatric	Large vessels	Diameter estimation and compliance of the inferior vena cava	Measure	Diameter
Abdominal	Bladder	Evaluate the volume/size of the bladder	Evaluation	Volume
Foetal/obstetric	Foetus	Identify pregnancy	Research	Presence

Table 5-2: Example of target identification workshop result

Target identification is the foundation stone upon which an entire training program was built. A long-term effort will be necessary to organize clinical studies for each of these targets and assess the superiority of diagnostic orientation with the echo-stethoscope versus typical examination. The work ahead is substantial; building a complete semiology for echo-stethoscopy will probably take years and the medical community will play a crucial role. Thus, early adopters of the echo-stethoscope will be invited to participate in clinical trials to collect and share images and diagnostic information. The results of these community-led activities will be submitted to peer-reviewed medical journals. In addition, images taken with the device will be made available online for the further advancement of science. The community manager explains:

the idea is to be able to share cross-section atlases, best practices, and content intended for the whole community.[...] This is how science progresses in echography; you share reference cross-sections with the community.

5.4.3.4 The end of the scope and business model stage

The business plan was defined at the end of this project stage, and a fully functional pre-industrial prototype (Figure 5-4) was produced. Segregation of roles between the NFP organization and the private entity was found to fulfill the initial vision of the commons: “Make a global health impact and promote the open ultrasound culture.”

During this project phase, the medical community made significant efforts to determine the device's technical specifications, its form, software interface, and potential targets. The development phase could start with an industrial partner that would convert the pre-industrial prototype into the final device and produce it. As the business development manager sums up:

We were no longer able to do fine electronics or complex mechanics on our own. It was no longer a maker affair [...], at the end of 2018.



Figure 5-4: Pre-industrial prototype

5.4.4 Development and test stage

At this stage, the IC was gone; community-led technical work was on hold, superseded by a professional manufacturer that would undertake manufacturing according to medical regulations.

From a commons perspective, activities were centered on advancing knowledge and understanding use cases in LMICs, cultural specificities, medical practice, training needs, and existing infrastructures. The community focused on adapting training material for users in the global south.

In anticipation of the introduction of this novel tool into various settings, ergonomic testing in the field and user tests in Benin were conducted, and the social impact in maternal health was assessed. The community manager explains:

[We] co-construct with future users and in particular health professionals. For the moment, we have targeted two contexts of priority uses: the Benin context for maternal and neonatal health and France in the context of emergency medicine. [...] We work in the workshop with midwives and doctors, and the idea is to prepare for the use of the device during consultations to anticipate potential resistance. What can we do to make this introduction as smooth as possible [...] and try to understand what this device will change in consultations.

Moreover, to obtain the CE-mark, clinical trials had to be conducted to validate the device's efficacy in assisting clinical orientation. They confirmed that the probe improved current clinical orientation and brought a medical benefit to patients.

5.4.4.1 Testing the medical device

The last step of an industrial development process is the medical device test. The organization must conduct a formative assessment of the device, a very formal exercise completed with the assistance of health care workers. They were asked to

use the device on volunteers, following a defined script, to validate the software and hardware of the product. A developer describes:

We realized with users, doctors, and interns that things were not very intuitive. That means updating the design and this will impact development of the regulatory process. Because this formative assessment is needed for the regulatory file, to describe what was tested with users to reduce potential errors that may result from it and to update the risk analysis.

5.4.4.2 Toward a medical knowledge common

Initial efforts identified twenty target organs that could benefit from a direct view inside the body during a clinical examination. For each target, the medical community contributed to producing a dedicated online training course to help identify signs of potential pathology during a clinical examination. A radiologist confesses:

Classical semiology is absolutely disjointed around this; I have several proofs of this. One thing that really makes me laugh is that there is a sign called lumbar contact for people with pyelonephritis. When you give an ultrasound probe to a doctor who has never done an ultrasound, you say: “Make lumbar contact,” and when you see where he is putting the probe, it is not on the kidney. That is very strange, but happens because the medical training doesn’t include visualization of the interior.

These training modules are also designed to draw attention to this nascent practice in order to convince additional health care workers to join the user community and create momentum around the practice. It is important to note that while it takes two years to train a radiologist, a diploma will be issued after two days of on-site training

plus complimentary online modules for the echo-stethoscope. The echo-stethoscope is “a simple tool” that does not cover all the functionalities of a fully-fledged ultrasound scanner but rather helps with diagnostic orientation. The training aims to democratize the use of the portable ultrasound scanner by non-specialists by explaining what can be seen and how that helps to understand a patient’s condition. Ultimately, by collecting and appropriately sharing this data, the medical community is contributing to an emerging medical information commons (Bubela et al., 2019) that is advancing the goal of a learning health system (Cook-Deegan & Dedeurwaerdere, 2006).

5.4.4.3 The end of the development and test stage

The development and test stage ended with the award of the CE mark after approval by the notified body. Henceforth, the private entity could sell the medical device. A training program adapted to low, middle, and high-income countries was made available. Hence, the product could be placed on the market and the project launched.



Figure 5-5: The CE marked medical device

Going forward, healthcare workers can seize the opportunity to develop new medical knowledge using this tool; already during its development, healthcare professionals expressed their intention to use the device in unexpected fields such as veterinary practice and physiotherapy. Various community members welcomed this sandbox approach to new uses:

We expect [...] that doctors will take hold of it, imagine and create new uses, that's for sure.

We support the deployment [of the probe] by observing usages and ensuring that users appropriate it and invent new usages too.

5.5 Discussion

This longitudinal case study describes an innovative medical project from inception to product launch. We observed that successive waves of supporting commons phased in and out according to the project stage since the very nature of the shared resource changed as the project matured. We proposed a process theory articulating this sequence of events from an innovation inception to its commercialization. We could also confirm the central role of the IC as an alternative way for innovations to bloom and, more generally, the role of commons constantly evolving to support project development.

Our first finding confirms Potts' (2019) theory that ICs are a combination of two commons: a CMTIR and a CEI. We described how these two commons sequentially appear before the initiation of the formal project and last until the end of the business model and scoping stage. Our study also contributes to the nascent literature on ICs and provides an in-depth description of activities and inner structure in the CMTIR that combines KCs for the software and knowledge part and a more traditional commons dedicated to hardware resource management. We advance the understanding of IC disappearance when project uncertainty is reduced. We observed how these two sub-commons produce valuable inputs for subsequent projects or development phases. The CEI materializes into a business plan and rapidly closes, as the business plan tends to be kept confidential. In contrast, the CMTIR continues to be helpful to the project. The intensity of information exchange diminishes gradually at the project level until it completely stops. We observed that information pooled and generated by this IC was made available to other projects in the form of a creative slack.

In the case study, we observed a complex OSPD where the value of an IC was obvious. It created cost-effective conditions for members to understand the complexity of transformative technology, produce the device in a heavily regulated environment, and bring it to market with the complex institutional design needed to

make it affordable and accessible globally. It would have been challenging to meet these conditions under purely start-up conditions, where finding investors for an affordable medical device would defeat the purpose of a market-based approach. Instead, the IC was the place where a hybrid business model matured, and concessions were made to bring the project to market while maintaining the open ethos of the mission and the community (Lemos & Giotitsas, 2021).

Scholars in the open design field have highlighted the limitations of merely describing OSH as an attribute of an object. Our case study concurs with recent models (Table 5-1), describing that OSH projects have two dimensions of openness, one related to the building process and another related to the openness of the hardware itself (Bonvoisin et al., 2021). In our case, the project's complexity—industry regulation, cash intensity, intellectual property—advocated for a closed product in order to comply with regulation and secure financial investment, while the aim of the project was to use open movements and an open development process to develop an affordable medical device that would improve global health.

We also contribute to the OSH literature stream with this case study; we describe why the level of openness changed according to the project stage and influenced the supporting commons' governance (Carpentier, 2021). These constant adaptations are aligned with what Bonvoisin et al. (2021) call a “local open process” as opposed to “consistent openness throughout the product development process.” Moreover, in the OSPD field, the absence of fully protective copyright mechanisms makes it very different from OSSD, where product protection and openness is enforced by copyleft licenses (Ackermann, 2009). Artifacts produced in an OSH project are not subject to copyright, only their design plans are protected. This protection could, therefore, easily be circumvented. Given these conditions, most OSPD projects frequently deliver technical bricks, sandboxes for hobbyists or prototypes⁴⁰, but very

⁴⁰ <https://certification.oshwa.org/list.html>

few end products are available off the shelf⁴¹. Thus, we advocate for the generalization of IC at an OSPD early stage to identify threats and opportunities and increase the chance of project success.

5.5.1 Limitations and suggestions for future research

For this case study, we focused on one of a number of projects that this OSH community was working on. We avoided parallel projects that were simpler, smaller, and not subject to commercialization challenges, such as equipment for training purposes. Therefore, our process model includes an arrow pointing to “Creative slack to support other projects” to account for this outflow of information and resources.

As with any case study, we obtained a deep understanding of that case over a long period of time, but our findings are limited and need to be corroborated. Similarly, we are conscious of the limitations inherent to purposive sampling bias and we interviewed individuals from inside and outside the community to limit that effect. Finally, the temporal bracketing strategy is known for its accuracy, but more case studies are needed to reinforce the generalization of our claims (Langley, 1999; Van de Ven & Poole, 2002). Hence, we invite scholars to adopt a similar temporal bracketing strategy to facilitate case study comparison and obtain more actionable insights for entrepreneurs expecting commons to be an alternative way to initiate OSPD “beyond market and state” (Bollier & Helfrich, 2014) or foster innovative project development (Potts, 2019).

We focused on the first iteration of the implementation of a medical device for our case study. However, we posit that for a subsequent version of the product and, therefore, a subsequent project development pipeline, an IC will not form. The community would instead tap into the creative slack to benefit from previous work

⁴¹ <https://www.pubinv.org/projects/>

and lessons learned to lower the project level of uncertainty. We invite scholars to conduct additional investigations to confirm our hypothesis.

Finally, after the product launch, we witnessed all the preparatory work to structure communication and knowledge sharing with the technical and medical community. An intense exchange of information is expected between medics working in this novel field of clinical examination. This activity will probably provide input to improve the medical device. In that case, healthcare workers could be seen as “people giving away their time and effort” without any monetary compensation, which is typical of open user innovation (OUI) (Hippel, 2005).

The ambition during the post-launch phase is to continue involving users in the product lifecycle and help evolve it. This is a fascinating aspect of OUI; the product gets refined in the hands of its “prosumers,” and it evolves based on their feedback and recommendations (Baldwin & Von Hippel, 2011). A community of users will continue to help improve the software and give field-based feedback to improve the probe. This user community will continue to pool the knowledge and information to support product development. Therefore, we invite scholars to study how an OUI community could form a KC to collect community insights for a novel iteration of project development during the post-launch phase of an OSPD. More work is needed to close the gap between ICs, OUI, and commons supporting private entities since all these facets of a similar endeavor are powered by an open process involving individuals not primarily motivated by profit.

6. Conclusion

This dissertation has examined how commons could be a suitable governance regime for complex OSH project delivery. We observed novel forms of commons, such as ICs and fascinating CBPP groups working on OSH projects. We also explored the motivations of individuals investing their time pro bono in long-term endeavors to co-create knowledge or build tangible artifacts.

In this final chapter, we summarize our findings and contributions from the previous chapters (Table 6-1). We also draw several practical implications for communities in the OSH field. Then we articulate our answer to our global RQ by combining our three different angles of study explored in the previous chapters (*How can commons support OSH movements and foster complex project delivery?*).

Finally, we set the stage for future research paths in these nascent fields.

Chapter	Main findings	Key contributions
3- How can Knowledge Commons adapt to industry regulations and place a product on the market?	<p>Commons governance flexibility is a key success factor to an OSH community development during complex project implementation.</p> <p>However, the inability to anticipate regulatory barriers can lead to unintended privatization of the commons.</p> <p>Partial privatization of a commons could be</p>	<p>This chapter presents one of the first case studies on an OSH project. We relied on the GKCF to describe the commons to facilitate comparison and generalization with other case studies (Frischmann et al., 2014).</p> <p>The chapter contributes to the literature by stating that forms of privatization could address commons' sustainability issues and should not not be limited</p>

	<p>temporary, and the shared resource may return to the commons.</p> <p>Dynamic assignment of volunteers from one project to another helps keep the momentum and the commons active during closed project phases.</p>	<p>to their alleged superiority in terms of efficiency for resource management (Partelow et al., 2019).</p> <p>This case shows that partial privatization could be a way to achieve a commons' objective in the absence of suitable solutions to industry regulation.</p>
<p>4- Do individual motivations influence knowledge sharing differently for two groups observed within web-based knowledge communities?</p>	<p>Frequent and occasional contributors in WKC share knowledge for different reasons, and we have measured the influence of these motivators.</p> <p>However, the <i>identification with the collective goal</i> stood out as a significant motivator for both groups.</p> <p>The internalization of extrinsic motivators plays a crucial role in long-term community participation, and</p>	<p>This chapter presents quantitative evidence to improve the survivability of online communities that struggle to sustain their activity and active member participation (Özkil, 2017).</p> <p>The chapter also shows that initial participation in a community may be subject to a cost-benefit analysis from the participant (Lerner & Tirole, 2002; Roberts et al., 2006).</p> <p>Longer-term participation is driven by the internalization of extrinsic motivators (Ryan &</p>

	<p>community managers should facilitate it.</p>	<p>Deci, 2000), explaining why this activity tends to become part of individuals' life (von Krogh et al., 2012).</p> <p>This chapter recommends active participation in online communities through the application of the SDT and its underlying factors supporting the internalization process of extrinsic motivators (Dedeurwaerdere et al., 2016; Ryan & Deci, 2000).</p>
<p>5- How do commons evolve to support the development of innovative projects?</p>	<p>Although commons are very flexible governance mechanisms, they can phase in and out an innovative OSH project development according to the development phase's requirements. We described these interactions in a process flow chart describing product development over a decade.</p> <p>ICs create cost-effective conditions to understand the</p>	<p>This chapter presents the first case study on ICs. It confirms Potts' (2019) theory that ICs are made up of several commons (two or more).</p> <p>Moreover, this chapter describes how these commons sequentially appear and disappear, complementing Allen and Potts (2016) regarding commons creation and Cohendet and Simon</p>

	<p>complexity of transformative technology. They are particularly suitable for identifying complex institutional designs needed by community-powered product development in regulated environments.</p>	<p>(2007) on IC disappearance in a creative slack.</p> <p>This longitudinal case study contributes to a better understanding of the evolution of commons' governance over a long period (Frischmann et al., 2014).</p> <p>Finally, this chapter closes the gap in the OSPD literature, illustrating the constant adaptations of supporting commons to project evolutions described by Bonvoisin et al. (2021) as a “local open process” as opposed to “consistent openness throughout the product development process.”</p>
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Table 6-1: Summary of this dissertation's findings

6.1 Chapter 3 - Open Source Hardware, exploring how industry regulation affects knowledge commons governance: An exploratory case study

States delegate powers to agencies that regulate industries in various fields (Hess, 2008). In Chapter 3, we tried to understand the influence of industry regulation on a KC and posed the following RQ: *How can Knowledge Commons adapt to industry regulations and place a product on the market?* Therefore, we conducted a case study on an OSH community developing an innovative medical device.

6.1.1 Summary of main findings and contributions

With this first case study, we contribute to a new field of research at the crossroads of regulated environments and open source innovations. We first describe the OSH movement and how it could become a game-changer for product creation and supply chains, as demonstrated successfully during the COVID-19 pandemic (Cutcher-Gershenfeld et al., 2021). The virtues of OSH projects are numerous; openness helps to build trust, and the reuse of standardized modules ease maintenance, documentation, and training (Gibney, 2016; Niezen et al., 2016), making it particularly suitable for LMICs (World Health Organization, 1985; WHO, 2010). These projects tend to have lower product development costs and facilitate innovation dissemination (Broumas, 2017). The open nature of this movement allows the onboarding of highly specialized or otherwise unaffordable expertise. Although OSH projects have much in common with OSS projects, they are more delicate to govern. They combine the flexibility, responsiveness, and low cost of the OSS side and the traditional constraints of collective work in the physical world. These projects are more cash intensive: They require infrastructures, volunteers have to gather in a specific location, and there is rivalry for the physical resources.

Moreover, artifacts a community is willing to build may be subject to various industry regulations.

Although some medical industry regulations has been waived⁴² during the COVID-19 pandemic, a complex medical device must fully comply to ensure patient safety. This requires a quality management system, several audits, and full accountability from the manufacturer, which is very challenging for a community of volunteers (Abuhav, 2018).

With this chapter, we find that the commons governance flexibility allows to support the community during the entire development process. However, the inability to anticipate regulatory barriers can lead to an unintended privatization of the commons. We confirm the seminal work of Partelow et al. (2019), stating that hybrid forms of privatization could be pivotal to achieving a commons' objective: in the case study chapter 3, delivering a medical device to healthcare workers. Moreover, privatization is often against communities' ethos cherishing transparency and consensus in decision-making (Ostrom, 1990). A divergence overcome by setting up an informal rule; at the project level, a commons could be privatized to complete the regulatory steps and reopened when a new product iteration supersedes the previous one. It avoids a digital commons tragedy and prevents underuse or under-maintenance of the existing KC (Greco & Floridi, 2004; Schweik & English, 2012).

This leads us to our second finding, that volunteers are the flesh and blood of a commons, and keeping a close link with them is fundamental. It is a life-or-death question to prevent them from disbanding and keeping the momentum with alternative projects during the regulatory and manufacturing phase. We found that portfolio management helps allocate resources against various projects within a commons so that when one project closes, the other continues. Volunteers can be

⁴² <https://www.insideeulifesciences.com/2020/03/23/mhra-issues-specification-for-a-rapidly-manufactured-ventilator-system-for-use-in-hospitals-during-the-covid-19-outbreak/>

dynamically assigned to other missions while production and regulatory steps are being dealt with, untangling the end of a project with the end of a commons.

6.1.2 Implications for practice

The initial approach to mimic the successful OSS model reached a limit with the new generation of OSH projects. These projects are more complex and subject to industry regulations. Assumptions inherited from the OSS environment, like open licenses to protect a product or simply the availability of adapted supporting software, are wrong (Bonvoisin & Boujut, 2015). Moreover, virtually building something and publishing the source code online is insufficient to deliver a tangible end product and make a significant impact. We will likely face future global crises similar to Covid-19, and OSH offers solutions and resilience (Baldwin & Di Mauro, 2020). However, in the absence of mature and straightforward solutions in this field, our first recommendation for practitioners is to thoughtfully assess the potential regulatory environment of their creation at a very early stage. Moreover, the community's objectives have to be defined relatively early on to establish an appropriate legal protection strategy (Beldiman & Fluechter, 2018; Marrali, 2014). Furthermore, rapidly opening up the project to other communities, fab labs, or relying on existing ICs has proved to be a successful strategy to deliver a final product (Bria et al., 2019).

In contrast, regulatory assessment could be easier if the community is more inclined to provide a sandbox or toolkit for others to build a simple object. Either way, we invite practitioners to approach specialized civil society groups (e.g., public invention⁴³, open regulatory⁴⁴, helpful engineering⁴⁵) because they can bring tremendous value and assist communities in anticipating intellectual property and regulatory challenges. Moreover, they can advise on patenting strategies, alternative

⁴³ <https://www.pubinv.org/2021/12/18/the-open-medical-technology-manifesto/>

⁴⁴ <https://openregulatory.com/>

⁴⁵ <https://helpfulengineering.org/>

mechanisms like branding, trademarks (Marrali, 2014), or copyfarleft licenses (Vieira & de Filippi, 2014). These interactions are instrumental in crafting a specific business model to sustain and develop the community (Kauttu, 2018; Pearce, 2017). Our second recommendation from chapter 3 is the importance of keeping the momentum with volunteers and dynamically assigning them to multiple OSH projects. Dynamic portfolio management offers volunteers various ways to contribute and keep them involved while a collaborative project is closed for a regulatory reason. Thus, stepping back from the project level to the whole community, privatizing part of a project, does not mean ending the entire commons. Moreover, as Partelow et al. (2019) described, privatization could be nuanced, including solely the physical resource, the governance process, or the intellectual property. Therefore, in the absence of suitable solutions from the regulatory environment or legal protection mechanisms, partial privatization could be a way to achieve a commons' objective. In this case, the manufacturing and distribution of a tool are private, while the commons focuses on the innovation and knowledge dissemination objective.

6.2 Chapter 4 - Understanding individual motivations among members of online communities

There are no commons without a community (Caffentzis & Federici, 2014; Mies, 2014), and discussions on commons omitting to consider community management are incomplete (Fournier, 2013; Laerhoven & Barnes, 2014). Chapter 4 focuses on community members' motivations and long-term involvement. With a quantitative approach, we try to answer RQ2: *Do individual motivations influence knowledge sharing differently for two groups observed within web-based knowledge communities?*

6.2.1 Summary of main findings and contributions

In Chapter 4, we challenge the assumption that community members are a homogeneously motivated population of individuals. A small portion of the WBK community is highly active, and a large majority merely access the commons posing few questions and sometimes commenting on shared content (van Mierlo, 2014).

Our first finding was obtained thanks to a SEM with a multigroup analysis. We confirmed that frequent and occasional contributors provide content for different reasons with different sets of motivators that we could compare in terms of intensity. Our second finding is that a cross-cutting and significant motivator stood out for both groups: identification with the collective goal. This construct borrowed from the SDT explains how members could progressively and increasingly be motivated to participate in a collaborative venture (Deci & Ryan, 2008). These long-term mechanisms are well known and should be leveraged by community managers to retain members and make their community more active. In detail, WBK members are motivated by the desire to learn, while experts genuinely want to share their expertise but do not use this activity as a revenue stream. This finding is crucial to improving the survivability of online communities that are often rapidly abandoned or demonstrate very little activity (Özkil, 2017).

In this chapter, we try to close the gap between the transactional way of seeing participation in online communities subject to cost-benefit analysis (Lerner & Tirole, 2002; Roberts et al., 2006) and an alternative perspective considering this participation as part of members' way of living as a social practice (Hausberg & Spaeth, 2020; Von Krogh et al., 2012). We could conclude that the cost-benefit approach might be more relevant for young communities. Social practice as a motivator to participate tends to develop progressively, supported by internalization factors: autonomy, self-efficacy, and social relatedness to the task. Thus, SDT might be more relevant in mature communities since it is more likely to find individuals who develop a stronger connection with the mission of the community.

6.2.2 Implications for practice

The survival of a community is bound to its ability to attract and retain members: They generate online content and drive advertisement revenue from traffic, providing the means to maintain the technical infrastructure and other administrative costs. Chapter 4 uses the SDT to understand why community members remain involved in communities over a long period. We observed that internalizing extrinsic motivations takes time but is a significant factor over the long run, confirming previous observations that long-term community involvement becomes part of individuals' personal life (von Krogh et al., 2012).

With this chapter, we bring a novel angle to online knowledge sharing activities not exclusively based on user experience or available features on the digital platform (Phang et al., 2009). Our recommendations to attract and retain active contributors are rooted into the SDT and we suggest that community managers leverage underlying factors supporting the internalization process of extrinsic motivators (Dedeurwaerdere et al., 2016; Ryan & Deci, 2000): i) Autonomy: We invite community managers to adapt their governance rules and improve user experience to boost their members' feeling of autonomy on the platform; ii) Self-efficacy: We recommend simplifying the process of making online contributions to facilitate participation as much as possible. Self-efficacy is progressive, and minimizing the barrier of the first contribution enables a virtuous circle as it is not only one of the significant motivators of our structural model (Figure 4-3) but also a supporting factor for internalizing extrinsic motivations (Kankanhalli et al., 2005; Legault, 2017); iii) Relatedness to the task objective: Community managers should try to create direct contact with major contributors and elaborate on the community's vision and mission, potentially proposing that experts take an active part in the community's governance.

6.3 Chapter 5 - How commons support innovative project development: Deep dive into the world of innovation commons

During an innovative project, the nature of the shared resource managed in a commons may change as the project evolves. Moreover, OSH product development combines tangible and intangible resources that must be governed separately (Basu et al., 2017). In Chapter 5, we observed an innovative OSH project over a decade to answer RQ3: *How do commons evolve to support the development of innovative projects?*

6.3.1 Summary of main findings and contributions

In Chapter 5, we continue the work initiated in Chapter 3 but extend the study of an OSH community over a decade. This longitudinal case study describes an innovative project in the medical field from its inception to product launch. We observed that successive waves of supporting commons phase in and phase out according to the project stages since the very nature of the shared resource changes as the project evolves. Thus, we detail how these commons' governance continuously adapts to these evolutions.

This chapter proposes one of the first case studies describing ICs. We confirmed Pott's (2019) theory that ICs are a combination of two commons: a CMTIR and CEI. We described how these two commons both appear before the initiation of the formal project and last until the end of the business model and scoping project stage. Moreover, we contribute to the existing literature on ICs by describing the disappearance of the IC when project uncertainty is reduced. We observed how these two sub-commons produce valuable input for subsequent projects or development phases. The CEI materializes into a business plan and rapidly closes as the business plan tends to be kept confidential. In contrast, the CMTIR continues to be helpful to the project. At the project level, the intensity of information exchange with the IC diminishes gradually until it completely stops. However, we

observed that information generated during the project and pooled in the IC is made available to other projects in a KC, what Cohendet and Simon (2007) call “creative slack.”

In the case study, we observed a complex OSPD where the value of an IC was obvious. It created cost-effective conditions for members to understand the complexity of transformative technology, produce it in a heavily regulated environment, and bring it to the market with a complex institutional design to make it affordable and accessible globally. These conditions would have been challenging to reach in a pure start-up mode, where finding investors for an affordable medical device defeat the purpose of a market-based approach. Instead, the IC has been where a hybrid business model matured, and concessions were articulated to bring the project to the market while maintaining the mission’s and the community’s open ethos (Lemos & Giotitsas, 2021).

Scholars in the open design field highlighted the limitation of merely describing OSH as an attribute of an object. Our case concurs with recent models (Table 5-1) describing that OSH projects have two dimensions of openness, one related to the building process and a second related to the openness of the hardware itself (Bonvoisin et al., 2021). In our case, the project’s complexity—involving industry regulation, cash intensity, intellectual property—pushed for a closed product to comply with regulation and to secure financial investment. The project’s objective was to advance a medical practice, improving global health with an affordable medical device thanks to open movements and an open development process. We observed that the project level of openness changes according to project stages as a consequence of the supporting commons’ governance (Carpentier, 2021). These constant adaptations are aligned with what Bonvoisin et al. (2021) called a “local open process” as opposed to “consistent openness throughout the product development process.”

Moreover, in the OSPD field, the absence of fully protective copyright mechanisms makes it very different from OSSD, where product protection and openness are enforced by copyleft licenses (Ackermann, 2009). Artifacts produced in an OSH project are not subject to copyright; only their design plans are protected. Thus, this protection could quickly be circled by adding minor modifications to the original design. Given these conditions, most OSPD projects frequently deliver technical bricks, sandboxes for hobbyists, or prototypes, but very few end products are available off the shelf. Therefore, we invite scholars to continue researching suitable protection mechanisms for OSPD projects and allow this movement to thrive fully.

6.3.2 Implications for practice

As theorized by Hayek (1945), innovation is not a question of investing resources in a well-identified issue or challenge. Instead, innovation emerges from the conjunction of various individuals from different fields sharing insights on a specific topic. Essential agoras for this process, fab labs are a new kind of place facilitating innovation emergence (Cohendet et al., 2021), acting as a hub for highly distributed, tacit, and uncertain knowledge. Increasingly, hackerspaces, or fab labs, are recognized as places where innovation happens (Leyronas et al., 2018) along with traditional “infrastructure for innovation” like academia and private companies. Rooted in hackerspaces, ICs offer low-cost access to resources and expertise, therefore we strongly recommend that practitioners tap into information polled in ICs at an early stage of their project to identify threats and opportunities to their endeavor and increase their chances of success.

Although these places have a strategic role in the innovation process, connection to diverse expertise from various fields is the key to learning from this first phase. Hence, we strongly encourage practitioners to connect to as many third parties as possible to improve their chances of success. We have empirical evidence that fab labs are more effective when connected to SMEs and large companies; they produce spin-offs and give broader opportunities to innovators to develop their projects

(Suire, 2019). We invite practitioners to tap into this notion of creative slack (Cohendet & Simon, 2007) which is full of “understandings gained through experience” generated and shared by other communities (Hess & Ostrom, 2007). Finally, we recommend that practitioners embrace a broader notion of OSH projects and adopt the OSPD vision. We observed that process and product openness are different but not antagonist notions in complex OSH projects. While the final product must be closed for regulatory reasons, the process could be successively opened and closed, depending on the project stage (Stirling & Bowman, 2021).

6.4 Overall conclusion

Commons have been instrumental governance regimes supporting many high-impact OSS movements in past decades. In this manuscript, we try to assess how commons could support significantly more complex projects in the OSH field. Furthermore, the OSH movement has to scale up and leave fab labs to spread worldwide and make an impact comparable to that achieved by the OS movement. We formulated this overarching ambition in our global RQ: *How can commons support OSH movements and foster complex project delivery?*

First, we assessed whether commons could play a significant role in helping OSH communities thrive in delivering complex projects. Our work intends to close the gap between the commons and the OSH literature. Thus, our studies dovetail with the recent OSH literature developments that disentangle the production process and product openness. Moreover, our findings strongly support the OSPD model with commons governing the production process, while product openness may not last, depending on the nature of the industry or the development phase (Chapter 3).

Commons often form to solve a market failure, where commoners could act as prosumers (Moor, 2021); in some of our cases, medical doctors became prosumers. Our objective was to advance the understanding of specific benefits these individuals within a commons could bring to complex project management and delivery. Therefore, we linked our work to project management concepts and

frameworks (Cooper, 2015) and proposed a comprehensive project process flow chart covering almost a decade of project development (Figure 5-2).

Furthermore, by selecting highly complex projects, we could observe acute tensions or dilemmas arising from community management, financial issues, and the regulatory environment. As mentioned, too-simple OSH projects are similar to OSS projects in their conception, with a vast majority of the work done online with digital tools to design an artifact (Troxler, 2010). We described the instrumental role of ICs in helping define a project's contours, assessing market feasibility while reducing project risks before the actual project starts formally. Then we witnessed how commons' institutional flexibility allowed the community to progressively adapt from a purely informal setup to increasingly complex institutional arrangements with multiple legal entities, as the project develops. Although the regulated environment pushed the community to close part of its development, the community-generated knowledge was transferred into a creative slack for the benefit of future projects, perpetuating the open movement ethos and maintaining community motivation (Chapter 5).

Thus, we could measure the importance of community members' adherence to the community objective as a central factor in individuals' motivation and, therefore, to project advancement (Chapters 3 and 4). Individuals are motivated by the community's collective goal and praise the openness of their work as synonymous with information sharing and learning. The unintended privatization of the commons could have ended the community (Chapter 3). However, members found their way between "market and state" with a closed medical device released to the public domain when superseded by a new device version. In doing so, the community's objective was maintained, and the community survived. Often, commoners cherish openness, and commons governance offers resilience to the community by allowing temporary arrangements such as making the fruit of the collaborative effort proprietary while keeping the production process open (Bonvoisin et al., 2021). This governance flexibility allows repurposing of

community members for alternative projects while segregating the community's roles between a not-for-profit and a for-profit organization.

Finally, once the product is launched on the market, commons naturally offer a forum for prosumers to continue to improve the product, provide suggestions for improvement, or support new users. An OUI community can share knowledge and contribute to the evolution of the product, drafting the contours of new specifications for a subsequent iteration of the product.

In sum, commons bring the institutional flexibility to constantly adapt to unforeseen challenges or changes in the legal status of the supported organization while maintaining the overall mission and objective that federates the work of commoners. We could observe commons' crucial role from a very early stage of product development with ICs. Then, during the development stage, their capacity to create ad-hoc institutional arrangements to structure the cohabitation of private and not-for-profit entities, providing the conditions for enough flexibility to survive to dynamic evolutions of the product's openness. Finally, over the long run, commons offer shelter for user communities gathering comments, suggestions, and recommendations to improve the product. Therefore, we can conclude that commons are an efficient governance regime for OSH and are particularly suitable for helping the OSH movement to thrive.

However, as described in Chapters 3 and 5, commons alone are unable to bring a product to market at this OSH ecosystem maturity stage. Some form of legal entity is almost unavoidable to realize significant projects, obtain or manage funds, or undertake professional manufacturing operations. As projects evolve, commons must be combined with a legal vehicle to address the two dimensions of OSPD. Commons facilitate information sharing and community management but cannot fully cover the product development side for regulatory reasons and, to a lesser extent, intellectual property limitations. This cohabitation of commons and private entities defines a third way between market and state, similar to the foundations supporting OSS communities (Schweik, 2014).

The OSH movement is recent, and its ecosystem is immature; scholars and practitioners must continue to build theoretical and practical enablers to help this movement thrive, leave fab labs, and scale up to create a credible alternative to the traditional modes of production. There is a need for legal innovation to fill the gap created by the absence of copyright mechanisms for OSH artifacts. In comparison, in the 1980s, the copyleft license was a decisive innovation that boosted the OSS development and led to its current success. Nevertheless, an effective license is just one of the many factors required to help an ecosystem mature. If we compare both movements, even after fifteen years of existence, the OSS movement was still proposing niche solutions praised by experts and geeks, and far from becoming the mainstream development movement fully supported by a majority of GAFAM members it is today (Google, Apple, Facebook, Amazon, and Microsoft).

6.5 Suggestions for future research

The future is not some place we are going to, but one we are creating.
The paths to it are not found, but made; and the activity of making them
changes the maker and the destination.

John H. Schaar (1981)

Throughout this thesis, we have observed how technological evolution created conditions for new commons to emerge. This new wave of commons blends the characteristics of previous commons, such as TC dealing with natural or tangible resources, and KC dealing with entirely intangible resources. Thus, we have explored the OSH environment to reveal an ecosystem where hardware resources are intertwined with software code and technical knowledge. We have witnessed how developing innovative products in this ecosystem could cause unintended dilemmas for commoners. Furthermore, this environment brings new challenges that could threaten the very existence of communities: inadequate protection of

intellectual property, scarcity of niche expertise, limitations on community size, and industry regulation. In this uncertain environment, commons have demonstrated not only that self-governance helps to achieve long-term protection and enrichment of shared resources but also that they constitute a credible alternative to traditional fully private product development. We have presented cases in which commons played a key role as alternative ways to develop innovative products. However, to fully achieve their objective and make an impact, the commons had to be formalized and institutionalized, from discrete tasks performed by volunteers to organized activities within various legal entities. This finding invites us to broaden our understanding of the factors that trigger the need to formalize commons, which, until now, mainly comprised the number of active members (Schweik, 2014). In the next sections, we propose future research paths to better understand the impacts induced by industry regulations on commoner expertise and on the legal status of the commons.

6.5.1 A new enclosure movement?

Historically, commons have been focused on and designed to solve free-rider dilemmas in a third way, that is, not reliant on private property or government-based solutions (Sanfilippo et al., 2021).

As discussed in this manuscript, managing free riders may not be the most central issue communities must face. For instance, commoners must make significant governance decisions to comply with medical regulations. Moreover, such regulation requires that either a moral person or individuals assume responsibility. Unlike their predecessors, digital or hybrid commons are under intense regulatory pressure to be “institutionalized,” but the absence of appropriate legal entities may impede such development. Moreover, commons’ volunteers are increasingly expected to become “professional commoners” to advance their projects in an increasingly regulated environment, for instance they must maintain quality

management systems and various data registers or conduct data privacy impact assessments.

After being attacked head-on by the first and second enclosure movements, regulation may be the next constraint forcing commons to evolve or to find appropriate tools to defend themselves. Some scholars think that we are witnessing the advent of a great regulatory movement, arguably a future threat to data and knowledge pooled in commons (Miller et al., 2008; Wong et al., 2022). This movement is not limited to data-related commons and may force various commons to institutionalize and commoners to professionalize. For instance, Oliveira et al. (2022) described how patients innovating to treat their disease have to be mentored to navigate health sector regulations and are sometimes invited to sell their innovations to large companies to develop them.

Therefore, we invite scholars to investigate whether commons are entering a new phase of evolution that entails a form of professionalization for commoners or a necessary institutionalization of the commons at some point in its development. More research is needed to identify potential alternatives and avoid a novel form of enclosure implied by these regulations.

6.5.2 Toward hybrid privatization

In this manuscript, we have discussed extensively the example of medical industry regulations that require documentation and complex systems not yet streamlined by technical solutions, preventing communities from delivering artifacts in a regulated environment. But, many other industry regulations are emerging that are applicable to a broader type of commons.

As a future research path, we think the most impactful would be to investigate the effects of the European Commission's (2018) directive to regulate personal data sharing and protect personal data privacy. The General Data Protection Regulation (GDPR)—conceived to protect consumers from marketing abuse and personal data

mining from the GAFAM—had a significant impact on many industries (Chico, 2018; Niebel, 2021; Shabani et al., 2021) and is becoming a new standard worldwide.

In a nutshell, GDPR states that a data subject (the owner of the data) has complete control over the data with a series of rights. Formal consent is needed to pool data, and this consent could be revoked at any time by any data subject, inviting directly or indirectly a new stakeholder to govern the pooling of personal information.

At the core of this liability, GDPR requires organizations to nominate a data protection officer to enforce the regulation, guaranteeing the appropriate use of personal data. Inability to comply attracts financial sanctions. This expertise is already mandatory, it forces community members to acquire the know how or outsource it to costly professionals. This regulation challenges the governance of data-centric commons, and its implication should be further assessed (Sanfilippo et al., 2021; Sanfilippo et al., 2019). We encourage scholars to investigate this field as it could have profound implications for commons and ultimately hinder the ability to share information freely with communities.

Although commons do not need a legal structure to operate and thrive, these regulations demand accountability from a legal entity or an individual. As exemplified in previous chapters, regulations increasingly push toward professionalizing informal commons. We encourage scholars to deepen our understanding of privatization as a tool to secure the objective of a commons instead of a dogmatic solution to the tragedy of the commons (Dulong de Rosnay & Le Crosnier, 2012; Partelow et al., 2019). Further research is needed to understand if legal entities will increasingly become mandatory to cope with all these regulations. Scholars should assess whether, as mentioned, commons are more at risk in the absence of an appropriate legal entity and, if so, how this could influence their development. Hybrid forms of privatization seem to be a promising way to address these institutionalization challenges; Partelow et al. (2019) studied many cases of

commons supported by privatization organizations (e.g., eco-certification in fisheries, seed patents, property rights in rangelands). We strongly encourage scholars to pursue research in this direction.

6.5.3 Barriers to information sharing and participation in communities

In Chapter 4, we observed the dynamic of participation in knowledge sharing and motivation with experts providing advice and information to a large audience. This is a great virtue of KC, champions of information accessibility and dissemination (Coriat, 2011). However, the digital divide prevents a large proportion of humanity, inadequately equipped, from accessing open knowledge and information (Cullen, 2001; Van Dijk & Hacker, 2003). This threat was identified long ago, and it is widely accepted that commons must not reproduce real-world inequalities (Fuchs, 2021). However, access to information is not the only challenge commoners may face. In particular, understanding instructions and documentation available online and implementing them in the OSH field sometimes require particular skills and expertise. The need for advanced skills brings inequalities and limits access and usage of these resources to experts or professionals. It also limits community size and participation (Bonvoisin et al., 2018).

Moreover, OSH projects are often poorly documented or rely on concepts unknown to newcomers interested in the topic. The absence of standardization in information formatting limits knowledge sharing and hinders potential contribution to a relatively limited part of the population (Bonvoisin et al., 2020). We invite scholars to contribute to this effort, promote best practices for sharing assembly instructions (Bonvoisin & Schmidt, 2017), and disseminate a unified standard to document and share OSH product specifications: the international standard IEC 82079-1:2019⁴⁶.

⁴⁶ <https://www.iso.org/standard/71620.html>

In recent years, a new promising paradigm has emerged, and scholars have forged a novel approach called “cosmo-localism” (Schismenos et al., 2020, 2021). This paradigm combines the strength of the digital world with hardware design in the digital sphere and small units of production like fab labs at the community level to “design global, manufacture local” (Priavolou et al., 2022). In these local sites, commoners are shown how to gain the tools and techniques needed to implement and realize their projects, improving knowledge transfer and therefore their chances of project success (Dekker, 2020). Ramos (2017) proposed the following definition: “cosmo-localism describes the dynamic potentials of our emerging globally distributed knowledge and design commons in conjunction with the emerging (high and low tech) capacity for localized production of value.” This division of roles simplifies the global environment by specifying what each group does and helps to facilitate access to information and execution. In turn, local communities have the equipment they need and means to convey the know-how; their role extends from a pure execution role to a learning and knowledge transmission role (Leyronas et al., 2018). We invite scholars to continue investigating how this combined digital and local commoning approach could constitute an efficient way of developing and disseminating OSH. Furthermore, assessing the scalability of this approach could constitute a critical stepping stone to the future development of the OSH movement. Finally, in a context of increasing pressure to professionalize some key activities within the commons, this practice could constitute a promising way forward to increase commoners’ awareness of these challenges and to train them accordingly.

7. Annexes

7.1 EFA values

Dimensions		Components						Communality
		<i>Cronbach's Alpha</i>						
		<i>.913</i>	<i>.840</i>	<i>.826</i>	<i>.788</i>	<i>.852</i>	<i>.855</i>	
Reputation Gain	GR1	.790	.086	.102	.060	.142	.080	.672
	GR2	.856	.038	.074	.065	.049	.108	.759
	GR3	.883	.068	.123	.040	.138	.069	.825
	GR4	.849	.084	.206	.062	.174	.039	.806
	GR5	.767	.111	.291	.028	.075	.083	.699
Knowledge sharing behaviour	KSB1	.115	.863	.112	.104	.102	.040	.794
	KSB2	.135	.877	.135	.067	.171	-.004	.839
	KSB3	.063	.877	.114	.024	.125	.033	.803
	KSB5	.024	.599	.101	.252	.016	.097	.443
Material Gain Expectation	EMG1	.199	.170	.782	.033	.052	-.008	.684
	EMG2	.146	.091	.749	-.020	.022	-.094	.600
	EMG3	.061	.100	.848	.004	-.002	.038	.735
	EMG4	.280	.088	.748	.058	.145	.102	.680
Identification with the collective goals	IDE1	.042	.122	-.032	.764	-.052	.039	.606
	IDE2	.020	.057	.048	.771	-.013	.153	.624
	IDE3	.055	.050	.010	.812	.054	-.101	.679
	IDE5	.085	.145	.031	.750	-.004	.113	.605
Knowledge self efficacy	KSEF1	.162	.182	.112	.066	.822	.266	.823
	KSEF2	.192	.169	.126	.039	.860	.208	.865
	KSEF4	.144	.071	-.016	-.107	.790	.065	.665
Enjoyment from helping others	ENJ1	.153	.096	-.016	.104	.290	.850	.851
	ENJ3	.154	.048	.014	.104	.193	.894	.873

Table 7-1: Factor analysis table

Loadings larger than .40 are in bold

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization. Rotation converged in six iterations.

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9. Summary

The world contains multiple types of individuals, some more willing than others to initiate reciprocity to achieve the benefits of collective action.

Elinor Ostrom (2000, p. 138)

The COVID-19 pandemic has reinvigorated the notion of a bundle of rights around ownership of COVID-19 vaccine treatments. Thus, among others, the French president has highlighted the need to decouple private companies' ownership of COVID-19 vaccines while being highly subsidized by public money from the worldwide population's right to treatment at an affordable price. Furthermore, with the consequences of the environmental crisis becoming increasingly visible, commons have been highlighted as inspirational governance models for the management of carbon emissions.

During the pandemic, individuals spontaneously came together to help healthcare workers. Demand for ventilators, masks, and medical spare parts was extraordinarily high, and supply chains were badly disrupted. These individuals formed Open Source Hardware communities to build what was needed locally. In turn, these communities proposed a novel mode of production that favored collaboration, production, and learning for individuals over the need to maximize profit. However, such an approach represents something of a gray area between "market and state" and is today relevant to a growing number of fields. As technology evolves, the capture of new resources becomes possible, causing social dilemmas, appropriation, congestion, and pollution issues. Commons governance mechanisms offer relevant solutions to these emerging challenges in an ever-increasing number of fields from global health and software and hardware development to outer space.

In this manuscript we focus on the Open Source Hardware movement, an innovative mode of production powered by groups of individuals building highly technical objects, blending software and hardware, and offering an alternative to proprietary innovations. We also spotlight recent members of the commons family—such as Innovation Commons, Knowledge Commons, and Hybrid Commons—to understand how they can best support this movement. Thus, addressing our overarching research question leads us to understand how commons can bring actionable solutions to support the open source movement and foster delivery of complex projects.

Apart from the introduction, literature review, and conclusion, our work comprises three chapters, each focused on a specific aspect of the commons: the shared resource, the community, and its flexible governance.

First, in an exploratory case study, we focus on the influence of industry regulation on an Open Source Hardware project. In this case, the shared resource is subject to medical industry regulation, resulting in substantial commons governance modifications. Our study uses the governing Knowledge Commons framework—a modified version of the institutional analysis and development framework—to untangle the interactions between resources, participants, and governance structures. We provide evidence that temporary privatization can be used as a way to protect and sustain a commons during an industrialization phase. We also demonstrate how a portfolio of projects is an effective and resilient way to help the commons survive this privatization step.

In our second study, we challenge the idea that communities are homogeneous and that their members are equally motivated to participate in knowledge-sharing activities. In this quantitative study, we collect data via an electronic survey of over 9,000 individuals. We rely on structural equation modeling and self-determination theory to obtain insights into long-term participation in digital commons. We introduce a novel construct to assess how community members' sense of identification with the community goal affects their knowledge-sharing behavior.

Moreover, our results reveal fundamental differences between participants' motivations for sharing knowledge, depending on their contribution level. Thanks to our refined understanding of these differences, we formulate more granular recommendations for managers of web communities.

Our last study is a longitudinal case study of an Open Source Hardware community over almost a decade of project development. We rely on a process methodology to articulate how the very nature of the shared resource within the commons can change over time. We observe several types of commons supporting an innovative project in the medical field and propose a process theory to explain the temporal order and sequence in which these commons form and disappear. We uncover the underlying mechanisms explaining why these supporting commons evolve and why they evolve as they do. Our paper contributes to the nascent literature on Innovation Commons and confirms existing postulates on their structure. We provide empirical evidence that an Innovation Commons is essential to the success of this project by creating the conditions needed to gradually professionalize the community and craft its unique legal structures.

Together, these studies offer a novel insight into the Open Source Hardware movement, highlighting its potential and limitations. Although auspicious and visible during the COVID-19 pandemic, this young movement also has shortcomings in regulated environments requiring hybrid governance models.

The risk for commons is real, and we wonder if we are witnessing the advent of a third enclosure movement. With this thesis, we describe how commons could make this collective mode of production a credible third way beyond market and state to create non-proprietary products, even in the most complex environments. Moreover, this manuscript invites a broader view of the cohabitation of commons and private entities. We advocate for a non-dogmatic approach above and beyond the alleged superiority of one model over the other. Empirical evidence shows that a combination of the two allows commons to deliver on their promises and achieve a

broad societal goal, while private entities offer a proxy to the world structured by market rules and regulations, not necessarily driven by profit maximization. Therefore, we invite scholars to join us and explore further this new frontier in the study of the commons: Open Source Hardware.

10. Samenvatting (Summary in Dutch)

De wereld kent verschillende soorten individuen, waarbij sommigen meer dan anderen bereid zijn tot wederkerigheid om de voordelen van collectieve handelingen te benutten.

Elinor Ostrom (2000, blz. 138)

De COVID-19-pandemie heeft de gedachte van een bundeling van rechten rond het eigendomsrecht van COVID-19-vaccinbehandelingen nieuw leven ingeblazen. Onder andere de president van Frankrijk heeft gewezen op de noodzaak tot ontkoppeling van de eigendomsrechten van particuliere bedrijven op met overheidsgeld gesubsidieerde COVID-19-vaccins en het recht van de wereldbevolking op een betaalbare behandeling. Daarnaast, nu de gevolgen van de milieucrisis steeds zichtbaarder worden, zijn *commons* naar voren geschoven als inspirerende bestuursmodellen voor het beheren van CO₂-uitstoot.

Tijdens de pandemie sloegen mensen spontaan de handen ineen om zorgverleners te helpen. De vraag naar beademingsapparatuur, mondkapjes en medische reserveonderdelen was buitengewoon groot en de toeleveringsketens waren ernstig verstoord. Deze mensen vormden zogenaamde open-source-hardware-community's om lokaal te vervaardigen waar behoefte aan was. Deze community's stelden op hun beurt een nieuwe productiewijze voor waarin samenwerking, productie en leren voor individuen belangrijker wordt gevonden dan het maken van zoveel mogelijk winst. Deze benadering vertegenwoordigt echter een enigszins grijs gebied tussen 'markt en staat' en is vandaag de dag relevant voor een groeiend aantal gebieden. Naarmate technologie zich verder ontwikkelt wordt het vastleggen van nieuwe middelen mogelijk. Dit leidt tot sociale dilemma's, toe-eigenings-, congestie- en milieuverontreinigingsproblemen. Mechanismen van commons-governance bieden relevante oplossingen voor deze nieuwe uitdagingen op een groeiend aantal

gebieden: van wereldwijde volksgezondheid en de ontwikkeling van software en hardware tot en met de (kosmische) ruimte.

In dit manuscript richten we ons op de open-source-hardwarebeweging: een innovatieve manier van produceren die wordt uitgedragen door groepen mensen die zeer technische objecten bouwen, software met hardware combineren en een alternatief bieden voor door eigendomsrechten beschermde innovaties. We kijken ook naar recente leden van de commons-familie – zoals *innovation commons*, *knowledge commons* en *hybrid commons* – om te begrijpen hoe zij deze beweging het beste kunnen ondersteunen. Met het beantwoorden van onze overkoepelende onderzoeksvraag kunnen we vervolgens begrijpen hoe commons bruikbare oplossingen kunnen bieden om de open-sourcebeweging te ondersteunen en de oplevering van complexe projecten te bevorderen.

Naast de inleiding, het literatuuroverzicht en de conclusie bestaat ons werk uit drie hoofdstukken, elk gericht op een specifiek aspect van de commons: het gedeelde middel, de community en de flexibele governance ervan.

Allereerst richten we ons in een verkennende casestudy op de invloed van industriële regelgeving op een open-source-hardwareproject. In dit geval is het gedeelde middel onderworpen aan regelgeving van de medische branche, wat leidt tot aanzienlijke wijzigingen in de commons-governance. Onze studie gebruikt het governancekader voor knowledge commons, een aangepaste versie van het institutionele analyse- en ontwikkelingskader, om de interacties tussen middelen, deelnemers en governancestructuren te ontwarren. We tonen aan dat tijdelijke privatisering kan worden gebruikt als een manier om commons tijdens een industrialisatiefase te beschermen en in stand te houden. Ook laten we zien hoe een projectportfolio een effectieve en bestendige manier is om de commons te helpen deze privatiseringsfase te overleven.

In onze tweede studie betwisten we het idee dat community's homogeen zijn en dat hun leden in gelijke mate gemotiveerd zijn om deel te nemen aan kennisdelingsactiviteiten. In deze kwantitatieve studie verzamelen we gegevens

onder ruim 9.000 ondervraagden via een elektronische enquête. We maken gebruik van structurele vergelijkingsmodellen en de zelfdeterminatietheorie om inzicht te krijgen in langdurige deelname aan digitale commons. We introduceren een nieuwe constructie om te beoordelen in welke mate het gevoel van identificatie met het doel van de community van invloed is op het gedrag bij het delen van kennis. Verder onthullen onze resultaten fundamentele verschillen tussen de beweegredenen van deelnemers om kennis te delen, afhankelijk van de mate waarin ze eraan bijdragen. Dankzij ons verbeterde inzicht in deze verschillen, formuleren we meer concrete aanbevelingen voor managers van webcommunity's.

Onze laatste studie is een longitudinale casestudy van een open-source-hardware-community over een periode van bijna tien jaar projectontwikkeling. We maken gebruik van een procesmethodologie om aan te geven hoe de aard van de gedeelde middelen binnen de commons in de loop van de tijd kan veranderen. We observeren verschillende soorten commons die een innovatief project op medisch gebied ondersteunen, en stellen een procestheorie voor om de tijdsorde en volgorde te verklaren waarin deze commons ontstaan en verdwijnen. We leggen de onderliggende mechanismen bloot die verklaren waarom deze ondersteunende commons zich ontwikkelen en waarom ze zich op die manier ontwikkelen. Onze paper levert een bijdrage aan de zich ontwikkelende literatuur over innovation commons en bevestigt bestaande vooronderstellingen over hun structuur. We leveren empirisch bewijs dat een innovation-commonsmodel cruciaal is voor het succes van dit project door de voorwaarden te scheppen die nodig zijn om de community gaandeweg te professionaliseren en te voorzien van specifieke juridische structuren.

Deze studies bieden samen nieuwe inzichten in de open-source-hardwarebeweging en belichten het potentieel en de beperkingen ervan. Hoewel gunstig en zichtbaar tijdens de COVID-19-pandemie, vertoont deze jonge beweging ook tekortkomingen in gereguleerde omgevingen die hybride bestuursmodellen vereisen.

Het risico voor commons is reëel en we vragen ons af of we getuige zijn van de komst van een derde enclosure-beweging. In dit proefschrift beschrijven we hoe commons van deze collectieve productiewijze een geloofwaardige derde weg naast die van markt en staat kan maken om niet-merkgebonden producten te creëren, zelfs in de meest complexe omgevingen. Bovendien nodigt dit manuscript uit tot een bredere kijk op het naast elkaar bestaan van commons en particuliere entiteiten. We pleiten voor een niet-dogmatische benadering die zich niet beperkt tot de vermeende superioriteit van het ene model boven het andere. Empirisch bewijs toont aan dat, met een combinatie van beide, de commons hun beloften waar kunnen maken en een breed maatschappelijk doel bereiken, terwijl particuliere entiteiten een volmacht geven aan een door marktregels en -voorschriften gestructureerde wereld, niet noodzakelijkerwijs gedreven door het streven naar maximale winst. Daarom nodigen wij wetenschappers uit om samen met ons deze nieuwe dimensie in de studie naar de commons verder te verkennen: open source hardware.

11. About the author



Pascal Carpentier was born in 1977 in France. At Drugs for Neglected Diseases Initiative, a Geneva-based NGO, he is responsible for Information Systems management and evolution.

With over 20 years of experience in both the private and public sectors, Pascal had the opportunity to develop disruptive e-Health solutions for cardiac disease therapies at Medtronic. He also has extensive experience with NGOs; as Head of Solutions Delivery, he implemented an innovative finance mechanism for UNITAID. Previously, as Information System Manager, he kickstarted GAVI Alliance and the Vaccine Fund information system.

Pascal graduated with a Master’s degree in computer science specialized in Business Intelligence at Ecole Supérieure Informatique Electronique Automatique (ESIEA) in Paris and completed a Master in Business Administration at Business School Lausanne (BSL). PMP® certified (Project Management Professional) and an active PMI Switzerland Chapter (Project Management Institute) member, he volunteers to organize conferences promoting best practices in project management. He is also passionate about commons and open source communities and currently enrolled in a part-time Ph.D. at Erasmus University in the Business-Society Management Department. He hopes his research will improve the understanding of how alternatives and open ways of production can help disseminate knowledge and innovations to craft a fairer world.

Publications

- Carpentier, P. (2021). Understanding individual motivations among members of online communities. *Les Cahiers du numérique*, 17, 153-183. DOI : <https://doi.org/10.3166/LCN.2021.006>
- Carpentier, P. (2021). Open Source Hardware, Exploring how Industry Regulation Affects Knowledge Commons Governance: An Exploratory Case Study. *International Journal of the Commons*, 15(1), 154–169. DOI: <http://doi.org/10.5334/ijc.1081>

Under Review

- Chapter 5 is under review at an international journal for publication

Conference presentations

- IASC Europe & CIS Colloquium on Commons and Policy 2022:
Healing and Law Making, Re-Creating Narratives
- IASC 2021 Knowledge Commons Virtual Conference:
Open-Source Hardware: Exploring how industry regulation affects Knowledge Commons
- 18th International Open and User Innovation Conference 2021:
Asymmetrical motivations among members of web-based knowledge communities
- Journée de l'innovation 2021 Les communs innovatifs : modèle d'affaires du XXIème siècle:
Open-Source Hardware: Exploring how industry regulation affects Knowledge Commons
- IASC 2020 Web Conference on African Commons:
Open Source Hardware a New Frontier for Knowledge Commons

12. RSM PT PhD series

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