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RODRIGO ARGENTON FREIRE

Open Design: Práticas atuais e implicações para a Arquitetura e o Desenho Urbano

INVESTIGATING OPEN DESIGN:

Current practices and implications for Architecture and Urban Design

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INVESTIGATING OPEN DESIGN: CURRENT PRACTICES AND IMPLICATIONS FOR ARCHITECTURE AND URBAN DESIGN

Tese de Doutorado apresentada a Faculdade de Engenharia Civil , Arquitetura e Urbanismo da Unicamp , para obtenção do título de Doutor em Arquitetura , Tecnologia e Cidade , na área de Arquitetura, Tecnologia e Cidade.

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Orientador: Prof. Dr. Evandro Ziggiatti Monteiro

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UNIVERSIDADE ESTADUAL DE CAMPINAS
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INVESTIGATING OPEN DESIGN

CURRENT PRACTICES AND IMPLICATIONS FOR ARCHITECTURE AND URBAN DESIGN

Rodrigo Argenton Freire

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Resumo

O conceito de Open Design (OD) tem atraído cada vez mais atenção entre estudiosos, comunidades, empresas e profissionais nos últimos anos. Os seus benefícios são frequentemente associados à democratização do projeto, customização em massa, rápida otimização de projetos e aos processos de inovação alternativos. No campo da arquitetura, exemplos que a adotam principios do OD já podem ser encontrados. As possibilidades vão desde o compartilhamento de componentes de baixo custo para a construção de casas (Wikihouse) até a fabricação de móveis (Opendesk) e ferramentas de agricultura urbana (AKER). No contexto de localidades mais pobres, o potencial da abordagem OD desperta interesse. Esta pesquisa investiga o conceito de OD como fenômeno emergente e suas implicações no campo da Arquitetura e do Desenho Urbano. Proponho uma análise de pesquisa multi-método, utilizando estratégias qualitativas e quantitativas no estudo do mesmo fenômeno e abordo quatro questões principais: (1) Como os diferentes aspectos de openness (abertura) afetam a fabricação de artefatos? (2) Como o OD se relaciona com o desenvolvimento sustentável? Quais são as limitações atuais e os caminhos possíveis para superá-las? (3) Quais são os desafios atuais para replicabilidade no OD e como superá-los? (4) Qual é a estrutura de uma comunidade colaborativa de OD? Como e por que os usuários colaboram? Com base nos resultados, é possível argumenar que o OD é uma maneira viável de mudar a maneira como arquitetos e urbanistas trabalham. Os obstáculos atuais, no entanto, precisam ser enfrentados antes que possam ser adotados por um público maior, especialmente nas comunidades mais pobres. Dos resultados transversais das quatro qeustões, quatro sugestões foram feitas: (1) a adoção de uma abordagem em metadesign, (2) a adoção de projetos modulares, (3) a educação para a abertura e (4) microfábricas móveis como infraestrutura urbana. A pesquisa contribui para as discussões sobre OD e tem como objetivo construir uma estrutura conceitual para a prática profissional dentro do OD.

Abstract

The concept of Open Design (OD) has recently gathered attention amongst scholars, grassroots, companies and professionals. Its benefits are often associated to the design democratization, faster improvement of design artifacts, mass customization and alternative innovation processes. A number of examples – in architecture - that adopt the principles of OD already exist. The possibilities refer to sharing low-cost and rapid-assembly components for building houses (Wikihouse), furniture fabrication (Opendesk) and gardening tools (AKER)). Given its potential benefits, the OD approach arouses interest in the context of poorer communities. This research aims to investigate the concept of OD as an emergent phenomenon and its implications to the field of Architecture and Urban Design. Little research on OD currently exists in the field of architecture and urban design. I propose a multi-method research analysis, using qualitative and quantitative strategies in the study of the same phenomenon. The research structure addresses four main questions: (1) How do the different aspects of openness affect artefact manufacturing? (2) How does Open Design relate to sustainable development? What are the current limitations and possible pathways to overcome such limitations? (3) What are the current challenges for replicability in OD and how to overcome them? (4) What is the structure of an OD collaborative community? How and Why users collaborate? Based on the findings, it is possible to argue for the viability of OD as a way to change how architects and urban designers work. Current hurdles however need to be tackled before it can be adopted by a larger audience, especially in poorer communities. From cross-cutting results of four RQs, four suggestions were made: (1) the adoption of a metadesign approach, (2) the adoption of modular designs, (3) the education for openness and (4) mobile microfactories as urban infrastructure. The research contributes to discussions on Open Design and aims to build a conceptual framework for the professional practice within the emergence of OD.

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Abbreviations

A&UD – Architecture and Urban Design

CC – Creative Commons (License)

CNC – Computer numeric control

DIY – Do-it-yourself

FSM – Free Software Movement

ICT – Information and Communication Technology

OD – Open Design

OS – Open Source

OSH – Open Source Hardware

OSS – Open Source Software

OUD – Open Urban Design

RWHS – Rainwater Harvesting System

SDG – Sustainable Development Goals

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Preface

This preface is dedicated to tell the story of this PhD research, which remounts to my Master's dissertation. For my master's, I studied the concept of compact cities and evaluated the role of compactness to define urban vitality, flexibility and resilience. However, it called my attention that self-made modifications were made in a large number of dwellings in some of the neighborhoods I visited, especially those with a higher degree of compactness, i.e. higher densities and higher social diversity. These modifications included increasing the dwellings size, by adding new rooms and floors, and changing the use, from residential to mixed or commercial. In fact, evidences show that over 80 percent of renovations or constructions are done without any formal supervision of architects or civil engineers. Are architects disconnected from this large number of potential clients? If so, how can architecture be more accessible? Surprisingly, the findings I have outlined have taken me to the concept of Open Design (OD), which is not really related to the compact cities debate.

Following these preliminary observations and based on my background in urban studies, some other questions were raised. Self-building processes are strongly connected to the private property; however, how can we guarantee the promotion of better living environments? Are good practices in architecture and urban design accessible to poorer communities? Can we, as professionals, adopt bottom-up approaches? Initially, my concern was to understand how Open (Big) Data and Open Source (OS) solutions could improve bottom-up approaches and be appropriated by architects and urban designers to solve common urban problems.

To explore these questions, some introductory research was conducted. It has taken me to studies on the use of information and communication technologies (ICTs) to promote democratic decision-processes. As we know, advances in ICTs are connecting societies, amplifying the possibilities for a true collaborative development of cities and providing a shift between professional and amateur relations.

A second reason for having the concept Open Design as the subject of this research comes from personal observations and a particular interest in beers. From 2013, I started noticing an increase in local breweries and bars serving craft beers. The reasons for that change were not clear at that moment (and are still not). However, I wondered whether it could be related to an increase in access to information, given the rise of information and communication technologies. Instructions on how to brew craft beer are now widely available in the Internet (see freebeer.org, for example) and recipes are shared, tested and developed in online communities. I cannot confirm whether the existence of such available information reflects in an increase of small/micro local breweries, changes in consumer behavior and in users who have brewing as a hobby. My personal experience as a single-time brewer, which resulted in a tasty Saison style beer, shows that opening knowledge is of great importance to make access to goods more accessible. If I can brew a good beer, can I build a good house?

As mentioned, this research was initially focused on the large quantity of data available because of ICTs and the use of virtual solutions (applications and software). Academic discussions and a reflective process on existing literature and emergent discussions in the field have taken me to a different perspective. First, the literature review on OS allowed me to identify existing initiatives related to the field of architecture and urban design. From the software perspective, in the development of tangible artifacts, some directly related to the field of architecture and urban design. Examples are: (i) the WikiHouse project, an OS project aiming at the development of building plans and assembling components; (ii) the Elemental Architecture Office, who shared the CAD source files of their social housing projects; and (iii) the Open Architecture Network, a former online OS community for developing ideas to improve living conditions in poorer communities.

Second, during my studies at the University of Aalto, I joined the New Global research project discussions where I was introduced to the concept of frugal and reverse innovations. Finally, discussions with Prof. Evandro Z. Monteiro, supported the shift from a research focused on intangible goods to the development physical artefacts. This PhD, therefore, reflects the need to investigate the concept of OD to the development of physical objects, identify its main limitations and comment on its viability as an alternative to link architecture and urban design professionals to the 80% of potential clients/users in a developing country context.

1 Introduction

In general, Open Source (OS) refers to the release of source code (programming codes, design plans, 3d models, bill of materials) for anyone to use, modify, fix and share. Successful experiences from Open Source Software (OSS) communities have originated new approaches to the development of tangible goods. Its success has been associated to its potential to improve innovation processes, optimize debugging and offer an alternative to traditional business models (LERNER; TIROLE, 2005; RAYMOND, 1999). Initially, the OS philosophy expanded to the design of hardware components, e.g. radio operators and Arduino. Currently, it has been explored in different fields, including furniture design (OPEN DESK, [s.d.]), architecture, machinery development (OPEN SOURCE ECOLOGY, [s.d.]) and biomedical products(OPEN BIONICS, [s.d.]). In time, the terms Open Source Hardware (OSH) and Open Design (OD) have been used to describe tangible artefacts in OS format.

The meaning of OS to the development of tangible artefacts has been addressed in academic literature (BOISSEAU; OMHOVER; BOUCHARD, 2018; FJELDSTED et al., 2012; RAASCH; HERSTATT; BALKA, 2009a) and its rise linked to the development of OS manufacturing tools, such as 3d-Printers and CNC-mills (KOSTAKIS; PAPACHRISTOU, 2014), and the expansion of Makerspaces and Fablabs (KOHTALA, 2015). It is not difficult to envision the OS phenomenon as an alternative to overcome challenges developing countries face. However, there is an existing gap in the literature when it comes to context of a developing country and further studies are needed to better understand its implications to sustainable development

A number of questions arise. Does OS have the potential to change how people design, consume and produce physical artefacts? How does it affect the traditional design practices based on individual demand? What are its implications to the field of architecture and urban design? Can it help communities to overcome challenging issues?

This research framework is developed based on existing gaps in the literature and a main research question is developed. What opportunities does OD offer for architects and urban designers to act on local issues?

Up to now, case studies have been conducted to (1) compare the OD principles to existing cases (BONVOISIN, 2016a), (2) understand its economics (DAFERMOS, 2015; RAASCH; HERSTATT, 2011) and (3) understand its development processes (FJELDSTED et al., 2012). The first question aims to investigate if OD can be explored in different fields and for different purposes, such as the development of objects to address place vulnerabilities. It focuses on the professional opportunities that OD might have for architects and urban designers. Using the Brazilian context as an example, can OD connect professionals to the 80% of the population which is not considered as their usual clients? What are the existing challenged to large-scale adoption of OD? What are the benefits to the society?

In addition to the questions above, three other questions are proposed to study OD: (1) *How do the different aspects of openness affect practice and artefact manufacturing?; (2) What kind of limitations exist in OD processes to promote sustainable development and what are the possible pathways to overcome such limitations?; and (3) How do users collaborate in existing OD cases? These are introductory questions which aim at familiarizing the researcher to the object of the study. These questions combine - in different levels – practice and theory, evidencing possible limitations or advantages to a widespread adoption of OD.*

How do the different aspects of openness affect artefact manufacturing? How does Open Design relate to sustainable development? What are the current limitations and possible pathways to overcome such limitations? What are the current challenges for replicability in OD and how to overcome them? What is the structure of an OD collaborative community? How and Why users collaborate?

1.1 Document Structure

The following document is structured in six parts (Sections 2 – 7). Section 2 is reserved to the literature review, where I discuss (1) historical examples of open innovation, knowledge sharing and open content before the existence of Open Design as a concept, (2) the origins of the Free Software Movement (FSM) and its implications to OD and (3) the existing definitions of OD. To conclude I highlight the principles and elements of OD based on existing literature.

Section 3 is complimentary to the literature review and introduces initial findings from the literature review. However, it focuses on the potential of OD as an alternative to (1) the way we design and manufacture things and (2) to architecture and urban design. In this section, I introduce the existing literature on OD regarding its potential links to design democratization, distributed manufacturing and alternative innovation processes and current interpretations of openness in the fields of architecture and urban design.

Section 4 introduces four research questions - RQs (Section 4.1) and describes methodological approach adopted in this research. For each question, specific methods and tools are briefly explained. Complete methods and tools are addressed in their respective Sections (5.1, 5.2, 5.3, 5.4). Section 5 therefore is dedicated to each one of the RQ proposed which are developed in a form of essays. RQ1 and RQ2 have been published at the Design, Art and Technology Journal (DAT) and the XXII International Conference of the Iberoamerican Society of Digital Graphics (SIGRADI). As for RQ3 and RQ4, both are in an under-review process at the Journal of Cleaner Production and First Monday. For the purposes of better structuring the thesis, I adopted the same format throughout the sections (including reference styles). However, the essays are written in the third-person.

In Section 6, I discuss the main findings of the RQs. I propose a new version for relating OD elements and principles, and identify four conditionings to the successful adoption of OD at a larger-scale by professionals in architecture and urban design, users and communities. Some of the conditionings contribute to general existing arguments in the literature whilst others are more focused on architecture and urban design. Finally, Section 7 presents the concluding remarks of this research, summarizes its contributions and indicates future research topics.

2 Literature review

2.1 Historical Review on Open Design

2.1.1 Open before Open

Between 30bC and 15bC, Marcus Vitruvius Pollio wrote "*De Architectura*", an architecture treatise dedicated to the emperor Caesar Augustus (63bC-14aD). The treatise consists on a compendium of Vitruvius's knowledge, based on previous sources, his personal experience and personal opinions on subjects such as city planning, architecture, building materials, geometry (symmetry and proportions), urban infrastructure, civil engineering and other machines (VITRUVIO, 1960). Vitruvius aim was to provide the emperor "*personal knowledge of the quality both of the existing buildings and of those which are yet to be constructed*" (p.4). Although dedicated to the emperor, it is possible to identify Vitruvius's motivation to share his knowledge to those who were not trained in architecture. The writer's intention to enable "*personal knowledge*" is noticed throughout the treatise when he instructs, details and explains the different building types, their correct orientation, proportion, geometry and materials, technologies for ducts, water pumping and catapults. In Book VI, he presents the building aspects for private houses and makes a singular view on the practice of architecture

> *"(...) But when I see that this grand art is boldly professed by the uneducated and the unskillful, and by men who, far from being acquainted with architecture, have no knowledge even of the car-penter's trade, I can find nothing but praise for those householders who, in the confidence of learning, are emboldened to build for themselves. Their judgment is that, if they must trust to inexperienced persons, it is more becoming to them to use up a good round sum at their own pleasure than at that of a stranger.*

> *Nobody, therefore, attempts to practice any other art in his own home – as, for instance, the shoemaker's, or the fuller's, or any other of the easier kinds – but only architecture, and this is because the professionals do not possess the genuine art but term themselves architects falsely. For these reasons I have thought proper to compose most carefully a complete treatise on architecture and its principles, believing that it will be no unacceptable gift to all the world" (VITRUVIUS, 1960, p. 167)*

It is unlikely that Vitruvius's expected to provide self-builders with the knowledge needed to perform the "grand art" of architecture. However, his mentions to the existence of self-builder householders and his intentions on sharing his knowledge deserve the highlight. His highly descriptive work enabled scholars, artists and architects to reproduce and interpret the building types he presented. There are, however, some limitations for reproducing his instructions linked to faulty translations, the contemporary cultural context and the willingness to support a specific theory on Vitruvius work (CLINI, 2003). Besides its contributions on the canon of what we call "Classical Architecture", the treatise also introduces a methodological approach to the practice of architecture. Heath (1989) calls it the Vitruvian method. According to him, it consists on a three-stage process. First, it starts with the selection of the building type (Temples, Private houses, Public buildings). Second, it defines the subtype of the building, e.g., the forum for public buildings. Finally, the symmetry standard is selected. From that, all other parts of the building are derived in accordance to geometric relations of proportion.

The motivations behind the "*De Architectura*", and its contents as well, allows me to consider it as a rudimentary but valid example of knowledge sharing (KS). Not only because it enables the appropriation of technical information to be replicated but also because it adopts a modular and systemic approach to solve building design issues (HEATH, 1989). It is not my intention to make a historical review on existing examples of KS. Instead, this chapter will address few examples to demonstrate the existence of such phenomenon, in different fields including architecture, before the establishment of recent concepts such as Open Source Software, Open Content and Open Design, which I introduce in Section 2.2. Furthermore, I highlight the importance of KS and collaborative processes to innovation and advances in technology before the emergence of advanced information and communication technologies. For that purpose, five examples are presented next. Three of them correspond to traditional, and general, examples in the literature of the potential benefits of KS. As for the other two cases, they refer to the field of furniture design, architecture and urban design reinforcing the idea that opening knowledge is not necessarily a recent practice and discussion.

2.1.2 Three cases of open innovation

The first and second cases here presented refer to the evolution of technology during the Industrial Revolution in the nineteenth century, in England and United States, respectively. The first case was initially explored by Allen (1983) and later detailed by other scholars (NUVOLARI, 2004; VON HIPPEL, 1988). More specifically, the authors explored two examples of technology improvements that took place in Cleveland's District and in the Cornish Mining District, both in England. The second case refers to Bessemer's innovation for the steel industry, in 1860's. It has been argued that such innovation enabled a quicker, more energy efficient and an increased volume capacity of the steel making process (MEYER, 2003). Finally, third case refers to the invention of two types of Polio Vaccine developed in the 1950's by Jonas Salk and Albert Sabin. Both inventions were made public which helped to attenuate disease cases worldwide, despite existing controversies regarding their safety.

2.1.2.1 Cleveland's District and Cornish Mining District

In Allen's study on collective invention (1983), he defines it as the "*free exchange of information about new techniques and plant designs among firms in an industry*". He illustrates collective invention by using, as an example, the evolution of blast furnaces after 1850 in Cleveland District, England. Informal and formal (in engineering literature) is argued to be the causes for rapid evolution of technology at that moment. Allen supports his vision based on three main propositions. (i) Incremental improvements of furnace heights and blast temperatures by different companies in a short period of time; (ii) Furnaces design replication by other companies, especially those outside the Cleveland District and; (iii) the possibility that inventors and companies profited from the release of technical information.

Nuvolari (2004) also discusses the advances on mining draining engines during the first years of the nineteenth century. After years of limited innovation on steam engines[1], caused by patent restrictions, mining industries from Cornwall, England, witnessed a great improvement in technologies for engine efficiency. The improvements were possible after the patent expired in 1800. In fact, according to Nuvolari (2004), the real reason for such improvements is the publication of a monthly journal for reporting technological innovations, characteristics, procedures and performance of engines. It helped the diffusion of best practices and stimulated engineers to compete for engine optimization (POLE, 1844, p.47). During this period, a major improvement was achieved by Richard Trevithick and Arthur Woolf, the high-pressure engines. In 1812, Trevithick design what came to be called the "Cornish boilers", a more efficient high-pressure steam engine than the existing ones at that period.

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[1]The mentioned steam engines were patented by Boulton & Watt, an engineering and manufacturing firm which developed a less coal consuming steam engine. The dependency on Boulton & Watt's engines ranged from 1776 to 1800.

2.1.2.2 Bessemer steel

The Bessemer steel consists on a steel making process developed by Henry Bessemer, in England. Meyer (2003) describes it as another example of collective invention, although significantly different than the blast furnaces and steam engine examples of the previous case. The Bessemer steel was patented in 1856 and, after being implement in the United States, ten years after, new improvements were made and also patented. However, instead of licensing each one of the patents individually, firms would the Bessemer Association, which held the patents. After joining the Association, the companies would gain access to a patent pool. Following improvements developed by the Associated firms were also made available to the Association. Meyer (2003) describes it as an example of collective invention, although restricted to firms that were part of the Bessemer Association. During this period, Meyer also shows that the creation of technical journals and professional associations were of significant importance to the development of new technologies.

2.1.2.3 Polio Vaccines

The case of the Polio vaccines dates the 1950s, when Jonas Salk and Albert Bruce Sabin developed two types of vaccines to fight polio. In 1954 Salk developed a protocol for the manufacturing of his polio vaccine, which used inactivated viruses. The fifty-five-page protocol was made public, however, it omitted specific details and obligated companies to compete to produce effective vaccines (OFFIT, 2005, p. 47). Although there were restrictions regarding the vaccine effectiveness and safety[2], the vaccine proved to work. Salk's vaccine was intensively funded by public investments, including private donations. Consequently, Salk claimed no patent rights. Albert Sabin's position was

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[2]Although Salk's vaccine proved to be effective, it relied on the different protocols developed by different laboratories for manufacturing it. In 1955, defective vaccines developed by Cutter Laboratories were approved and injected in several children in United States. The result was that several children were paralyzed.

opposite to Salk's on using inactive viruses. Sabin believed that using attenuated viruses would not only work better but present less risks. His vaccine was used in 90 million people in Russia. Although it was unstable, it replaced Salk's vaccine in United States from 1961 to 1998, and during the 1970s most of the world was using Sabin vaccine (BLUME; GEESINK, 2000). Sabin also did not claim patent rights for vaccine. One could argue that unpatented vaccines are not commercially attractive. However, as enthusiasts of open source in drugs development point out, profits may be smaller but so is the risk (MAURER; RAI; SALI, 2004).

2.1.3 Openness in design

2.1.3.1 Autoprogettazione

The book "Autoprogettazione", by Enzo Mari (1974), an Italian furniture designer, consisted of a collection of simple furniture designs published as a manifesto against mass industrial production. The catalogue includes "easy-to-assemble" furniture from easily accessible materials, such as nails and rough boards. Regarding the simplicity of the designs, Mari stated

> *"Difficult? Not at all (...) there is no need for glue, no need for particular joints, the method is extremely simple and is the one used by carpenters to build their work benches and scaffolding, a semi-spontaneous technique that can be easily picked up (...)"* (MARI, 1974 p. 33-35)

When the catalogue was launched, the reader had two options in order to make his own furniture. He could build it from scratch, using rough boards, sawing and finishing; Or, he could buy a kit of finished planks from a factory in Bologna, which supported the Mari's project. Figure 1and Figure 2 show one of Mari's designs.

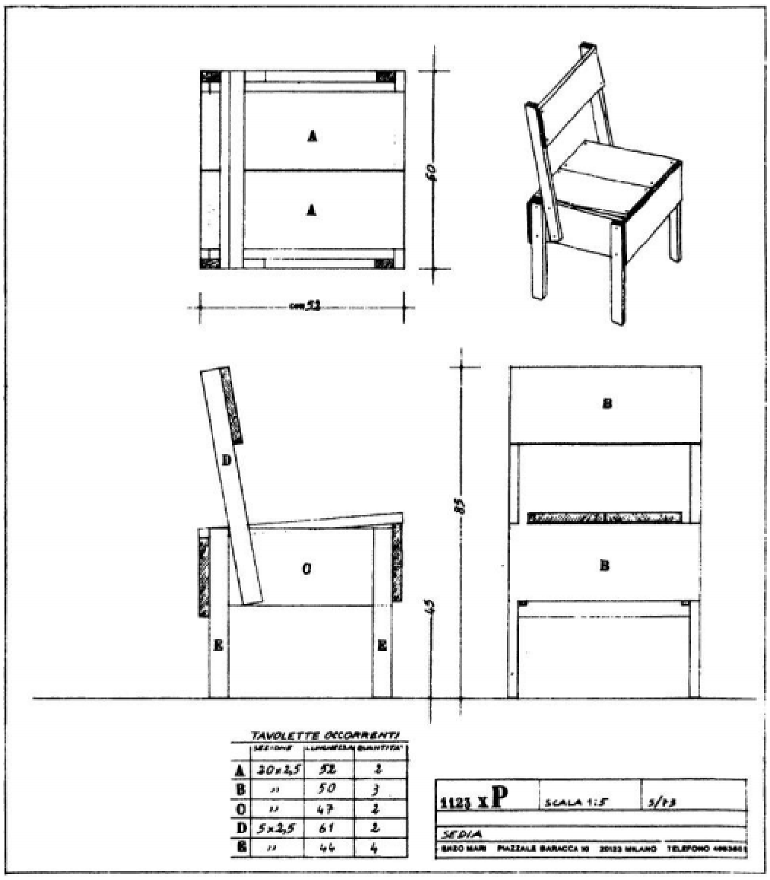

Figure 1 Enzo Mari's chair design shared in "Autoprogettazione"
(Source: Enzo Mari, 1974)

Figure 2 Built table based on Mari's design presented in Figure 1.
(Source: Enzo Mari, 1974)

2.1.3.2 A pattern language

In the 1970's, two books "A Timeless Way of Building" and "A Pattern Language" were written by Christopher Alexander. These books are a result of years of collaborative research in (i) understanding the aspects related to the building process and (ii) constructing a pattern language based on that knowledge. Several reasons can be pointed regarding the importance of both books for the field of Architecture and Urban Design. However, I will highlight two of them, related to the topic of this research. The first one refers to the possible applications of the patterns described by the author:

> *"(...) This language is extremely practical. (...) You can use it to work with neighbors, to improve your town and neighborhood. You can use it to design a house for yourself, with your family; or to work with other people to design an office or a workshop or a public building like a school. And you can use it to guide you in the actual process of construction."* (ALEXANDER et al., 1977, p.x)

In this case, the intention is that by using one or a few of the 253 patterns described, one could possibly adopt best-practice solutions to design his own house – although Alexander also highlights some patterns are defined based on hypothetical assumptions (ALEXANDER et al., 1977, p.xv). The second reason refers to the design process based on the use of the patterns. Although the patterns are, per se, a valuable contribution, it is the instructions provided that enable them to be incorporated in the design process. The instructions follow a very logical structure:

1. Introduction to a specific issue for pattern n°173 (Garden Wall):
2. Example "Gardens and small public parks don't give enough relief from noise unless they are well protected"
3. Explanation of the problem
4. Introduction to design alternatives and examples
5. Introduction to other related patterns
6. Example: Patterns Positive Outdoor Space (n°106), Hierarchy of Open Space (n°114) and Zen View (n°134)

Interesting to the subject of this research is that the patterns act at the abstract level, i.e. do not define a specific solution and the related technical drawings (nor it would be desired). Instead, it helps the reader to understand why, how and when such patterns should or could be applied.

2.1.4 General Remarks

The cases illustrate KS as a long-term phenomenon from a wide range of sectors. The definition of KS consists of the conscious act of making knowledge, information and know-how available to others within specific organizations (IPE, 2003), between organizations (LEE, 2001) and without defined audience (CUMMINGS, 2004). The cases of different nature illustrate the multiple possibilities for knowledge sharing, which contribute to the development of a definition for OD.

The first one refers to the actors which are part of the KS process. The first two examples (Cleveland's and Cornish Mining Districts, and Bessemer steel) consist of examples of business-to-business (b2b) collaboration. The examples show two possible alternatives for KS: (i) either by freely releasing technical innovations, drawings and specifications or (ii) through a consortium of companies with access to a shared patent pool. As for the Polio vaccine development, the actors are related to research and development, the industry and the public sector. It is also important to highlight the role of public donations – maybe a precursor of the Crowdfunding movement? - to the vaccine development. In the case of Enzo Mari's *Autoprogettazione* it represents a case of individual action towards the dissemination of inventions or technical knowledge to be directly used either by final consumers or by an intermediate company which sold the assembling components. And, finally, Alexander's patterns are directed either to skilled design professionals (architects and urban designers) and to an unskilled audience in general.

Motivations and benefits are also different. The cases I have introduced of industrial innovation, for example, were privately funded/developed aiming at increasing production efficiency, reducing costs and, thus profit earnings. In the case of the Polio vaccine development, it was strongly supported by government financial support and public donations, for solving a public health crisis (BLUME; GEESINK, 2000). Although produced by pharmaceutical companies, the decision of not patenting the vaccines benefited the public in general by keeping its production costs low. As for the release of technical drawings by Enzo Mari, it was part of a strong political manifest, although, he also innovated by adopting a business model based on pre-made kits ("pack of planks") supply. These kits were intended for customers who wanted to build his designs but couldn't (or didn't want to) produce the planks from raw timber. In fact, a number of current open source hardware projects (OSH) adopt the kit-supplier as a business model (PEARCE, 2017). Finally, the pattern language is considered much more of a piece of process than a piece of design. Possible implications in professional practice and lay users is that it optimizes the design process and increases chances for successful choices. It is not by chance that the pattern language concept has been adopted in different fields for tackling complex and recurring issues, such as in software development (BECK et al., 1995).

Finally, the third aspect refers to sharing restrictions of each case - from a nonrestrictive usage to limited restrictions for associates. The Bessemer's steel example is the one with the most restricted audience, i.e. limited to a group of companies. On the opposite direction, Enzo Mari's designs are free for anyone to reproduce them, although he restricts its use by "*manufacturers and traders*". Table 1 illustrates the cases and their specificities to knowledge sharing processes.

The cases illustrate the existence of KS before the development of advanced information and communication technologies (ICTs). Merges (2005) also presents some historical references while commenting on the OSM. He adopts the term "virtual guild" to refer to OSM. The term comes from the medieval guilds which he defines as *"bottom-up" institutions: norm-based groups which developed their own internal governance rules."* Besides that, he argues that "bottom-up" structure effectively promoted the generation and sharing of information and techniques.

Table 1 - Open Innovation cases in history

Cases	Actors	Audience	Motivations / Benefits
Blast Furnaces and Steam Engines	Collective collaboration (Companies)	Other companies and individual inventors (Open)	• Private investment in technological innovation • Release of technical information for profits increase
Bessemer's Steel Proccess	Collective collaboration (Companies)	Companies from the same Association (Closed)	• Private investment in technological innovation • Patent pool for Associates
Polio Vaccines	Research and Development	Laboratories and Researchers (Open)	• Government funding and public donations • Decrease of Vaccine production costs
Furniture Design *"Autoprogettazzione"*	Individual development	Undefined (Open)	• Anti-industrial manifesto (non-commercial) • pre-made kits for sale (commercial)
A Pattern Language	Collaborative Research	Professionals and lay users (Open)	• Provide lay users with design patterns for specific issues • Introduce the patterns method to professionals

Existing cases of Open Innovation and highlights specificities of each case based on main actors, audience and economics.

Much of the aspects presented in those cases are also present in current practices of OD, e.g. the different actors involved, motivations and sharing restrictions. These aspects contribute to the definition of OD, which will be introduced in Section 3. As for ICTs, studies have discussed their role as enablers of KS (PANAHI; WATSON; PARTRIDGE, 2013), in organization studies (CUMMINGS, 2004; IPE, 2003; LEE, 2001), software development (OSTERLOH; ROTA, 2007; VON HIPPEL; KROGH, 2003), frugal innovations (SMITH; FRESSOLI; THOMAS, 2014), product design (KOSTAKIS et al., 2015; KWON; LEE, 2017; RAASCH; HERSTATT; BALKA, 2009) and community resilience (OWEN; GOLDIN, 2015; RIMA; HANSPETER, 2013). It is, therefore, important to understand how ICTs contributed to the emergence of KS based concepts, organizations and initiatives.

2.2 From Free Software to Open Everything

The Free Software Movement (FSM) dates the 1980s, after the popularization of personal computers and advances in ICTs, e.g. ARPANET (LERNER; TIROLE, 2003). In the 1970s, universities and research laboratories from different locations were connected through the ARPANET, a high-speed computer network developed by the U.S. Defense Advanced Research Project Agency (ARPA), in 1969 (VON HIPPEL; KROGH, 2003). The network allowed programmers to exchange software code and information in a cheaper and faster way. In 1983, Richard Stallman, a programmer at MIT's Artificial Intelligence Laboratory, launched the GNU Project, a Unix-compatible software system[3], and, in 1985, he created the Free Software Foundation (FSF). The GNU Project was motivated after access restrictions were applied, by a commercial company, to the source code of a software developed by MIT programmers (ELLIOTT; SCACCHI, 2008; LERNER; TIROLE, 2003; VON HIPPEL; KROGH, 2003).

FSM is based on a political and philosophical perspective which stands on "*four essential freedoms*" (GNU, [s.d.]a)*:* (1) freedom to run the program, (2) freedom to study and change the program in source code form, (3) freedom to redistribute exact copies of the program and, (4) freedom to distribute modified versions of the program. However, it is important to highlight the existing misinterpretation of the term "Free" adopted in FSM. In English, "free" can refer either to costs or freedom. In Free-Software, free stands for freedom. In other words, free software is not only subject to a price (fee) but it's selling is also encouraged, as long as the four freedoms are respected (GNU, [s.d.]b).

The GNU operating system (OS) involved the adaptation of existing free software and the development of new free software and other components, e.g., text editors, command processors, mailers etc. In 1991, when most of the system was

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[3]The origins of GNU (Gnu's not Unix) is documented at the GNU's Page https://www.gnu.org/gnu/initial-announcement.html.

complete, Linus Torvalds released Linux, a kernel compatible to UNIX. The kernel was last step needed to complete the OS, which is now known as GNU/Linux[4]. The modular approach adopted in the development of the GNU system is considered an important factor to its success and posterior improvements. It allows faster development, module recombination, innovation through competition and reuse of codes (NARDUZZO; ROSSI, 2008). After the release of GNU/Linux, the free approach allowed it to be improved by many other programmers.

Although the Linux kernel helped to make the GNU system possible, it was followed by a rupture within the Free Software Movement. The ambiguity of the term "Free" and the political-philosophical approach of the FSM resulted in a debate among programmers, including Linus Torvalds. Their aim was to find an alternative less restrictive to software developers/programmers and more appealing to business. In 1998, the term "Open Source" (OS) was coined and the Open Source Initiative (OSI) was founded (MARGONI; PERRY, 2010). There are similarities between the Open Source and the Free Software definitions. The term "Open", for instance, also reflects the concept of freedom. Studies also associate OS to collaborative methods and development processes (MOCKUS; FIELDING; HERBSLEB, 2002; SHAH, 2005; VON KROGH; SPAETH, 2007) and to emerging innovation models (LAKHANI; VON HIPPEL, 2003; VON HIPPEL; KROGH, 2003). The full definition of Open Source adopts a set of ten criteria established by the OSI. Later, the terms FLOSS (Free Libre Open Source Software) and FOSS (Free Open Source Software) were defined to address software which meet both definitions of free software and open source software.

Following the potential of the OS model as a viable alternative for innovation processes and businesses within the software communities, other initiatives and definitions were developed in the late 1990's and early 2000's. Such initiatives and

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[4]The GNU/Linux name refers to the GNU operating system which uses Linux as a kernel. However, the system is often miscalled simply Linux. Complete discussion is found at: https://www.gnu.org/gnu/linux-and-gnu.html

definitions expanded the Open Source movement, so far restricted to the software development. The Open Content concept was initially discussed in 1994 (STUTZ, 1994) but established only in 1998 after the creation of the Open Content Project. It refers to *"anything that isn't executable"* (WILEY, 1998) e.g., photography, literature, music, videos, educational material and others. In 2001, the Creative Commons (CC) was launched and replaced the Open Content Project in 2003. The CC was established as a non-profit organization aimed at developing and supporting technical infrastructure to enable the dissemination open content. The Wikimedia Foundation is a prominent example of open content which uses the Creative Commons Licenses to its contents.

Other terms have been created and used to describe the forms that people and communities collaborate to the development of specific projects, products, software and how the knowledge collectively created is shared. The use of different terms can be fuzzy and is mainly limited to the differences between the industry sectors they refer to. Open Data, Open Knowledge, Open Research and Open Manufacturing are examples of terms linked to the OS definition but limited to specific objects. In 2004, for example, the Open Knowledge Foundation (OKFN) was founded as a non-profit organization aimed at making knowledge, information and data available as open content.

In parallel to the evolution of concepts from software to content, initiatives regarding the development of hardware and tangible goods took place in the end of the 1990s. From 1997 to 2000, we can observe an increasing number of initiatives focused on open hardware development: Open Hardware Certification Program, Open Hardware Specification Project (OHSpec), Open Design Circuits, Open Source Hardware and Open Design Foundation (OSHWA, [s.d.]; VALLANCE; KIANI; NAYFEH, 2001). Many of the initiatives no longer exist and others were incorporated into newer versions. In 2007, the Open Graphics Project gave origin to the Open Hardware Foundation (OHF). As the Open Source Hardware community grew, in 2010, a collaborative process defined Open Source Hardware as *"hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design."*

(OSHWA, [s.d.]). In 2011, the Open Source Hardware Association (OSHWA) was created after community controversies. Since 2000, a growing number of Open Source Hardware projects have been developed by businesses, scholars and enthusiasts.

Initially linked to the development of electronic components, such as Arduino and Raspberry Pi[5], the possibility of applying the OS model to the development of other tangible goods called the attention of researchers, enthusiasts and practitioners from other sectors (DAFERMOS, 2015; FJELDSTED et al., 2012; KOSTAKIS et al., 2015; RAASCH; HERSTATT, 2011; RAASCH; HERSTATT; BALKA, 2009). von Hippel & von Krogh (2003) illustrate it by comparing the freely reveal of software code to the freely reveal of CAD designs. Other examples include fashion, biotechnology, and pharmaceuticals industries (LAKHANI; PANETTA, 2007) and machinery (KOSTAKIS et al., 2015).

2.2.1 Intellectual Property and Licenses

In Free/Open movements, the approach to knowledge is similar to the approach to the commons introduced by Garret Hardin (1968). To secure a sustainable management of such resources, Hardin proposes either privatization or state control. However, the approach to knowledge commons takes an alternative path. Ostrom (1990, p. 15-22) proposes local, self-organizing units[6], as better alternatives to govern the commons. The adoption of licenses in Free/Open movements is, therefore, a tool to ensure the four freedoms initially stated by the FSF, in 1995 (VALLANCE; KIANI; NAYFEH, 2001).

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[5]- Arduino and Raspberry Pi are, respectively, a micro controller and a microcomputer developed under Open Source licenses applied in several types of projects, e.g. automation, sensors and controlling 3D printers and CNC mills.

[6]- Ostrom proposes eight essential principles to rule the existence of self-organized institutions: (1) Clearly defined boundaries, (2) Congruence between appropriation and provision rules and local conditions, (3) collective-choice arrangements, (4) monitoring, (5) Graduated sanctions, (6) conflict-resolution mechanisms, (7) minimal recognition of rights to organize and (8) nested enterprises – in the case of larger systems.

If new knowledge is freely shared to anyone without any restriction, how to preserve the fundamental principles of freedom? If no license is attributed to new knowledge, is it safe to make use of it under the four types of freedom? The idea is that the owner of the intellectual property rights has to officially authorize the use, modification and redistribution of his product under certain conditions. In this sense, the first version of the General Public License (GPL) was released in 1989 by the FSF – currently FSF uses the 3.0 version of GPL. It is important to note that similar discussions which originated the foundation of the Open Source Initiative also resulted in the development of different license types other than the GPL. In Table 2., I introduce the Creative Commons License which is commonly used in the release of physical objects documentation or creative/artistic works.

Table 2 - Creative Commons Licenses. Source: (CREATIVE COMMONS, 2017)

Variations	Description
CC0	Enables the holder of copyright or database rights to waive all the interests and completely share them in public domain
CC BY	Enables others to share and adapt/modify copyrighted material but (1) credits must be given to the original creator
CC BY-SA	Enables others to share and adapt/modify copyrighted material but (1) credits must be given to the original creator and (2) modified versions must be shared under the same license as the original
CC BY-ND	Enables others to share but (1) credits must be given to the original creator and (2) restricts modification of original content
CC BY-NC-SA	Enables others to share and adapt/modify copyrighted material but (1) credits must be given to the original creator and (2) restricts commercial purposes
CC BY-NC-ND	Enables others to share and adapt/modify copyrighted material but (1) credits must be given to the original creator, (2) restricts commercial purposes and (3) restricts modification of original content

The Creative Commons Licenses are built in a modular approach (CC, BY, SA, ND, NC) and provides a standardized way to grant copyrighted permissions to their content.

2.3 Open Design: Elements and Principles

In 1999, the Open Design Foundation (ODF) was established to support, evaluate and distribute open design projects (VALLANCE; KIANI; NAYFEH, 2001). The term OD emerges as a complement to the Open Hardware definition by formally introducing the approach of openness to creativity sectors. Originally, it referred to the freedoms of the FSM, later adapted by the OSI. Katz (2011), for instance, highlights the importance of the freedom to use, change, study and make derivative works of the original design. Currently, OD is subject to different approaches within scholarly, communities and companies. Commentators of OD understand the revealing of information as a consciously intention to achieve collaborative development for either market or non-market purposes (RAASCH; HERSTATT, 2011); Bonvoisin and Boujot (2015) explore online collaborative processes; And Boisseau et al. (2018) propose that OD depends on both the design process and the revealing of documentation. Some formal definitions have been proposed. The Open Knowledge Foundation (OKFN, 2012), for example defines it as a *"design artifact whose source documentation is made publicly available so that anyone can study, modify, distribute, make, prototype and sell the artifact based on that design"*. The OKFN's definition focus, therefore, on the publicity given to the source documentation. At the same time, it also assumes the existence of different levels of openness considering the documentation format and the design processes. A more comprehensive approach, therefore, could consider OD as *"provid[ing] public access to participation in the design process and to the product resulting from that process, as well as the data created in the design process, including technical details and other data and content gathered or generated during the process."* (AITAMURTO; HOLLAND; HUSSAIN, 2015).

However, it is important to discuss whether collaborative development is a precondition for OD. Supporters of such understanding collaboration argument that OD is enhanced collaborative processes. In *'The Cathedral and the Bazaar'*, for example, Raymond (1999) explores the idea that given a high number of testers and collaborators issues are easier to be identified and faster to be fixed. He calls it "Linus's Law". This is a particular condition to software development although criticisms to the law also apply (WANG; SHIH; CARROLL, 2015), e.g. disparity of expertise may result in redundant and invalid bugs reports. As for the development of physical components, however, one can argue that constant revisions are neither necessary nor desired. The first reason is that in the case of a design object, as it happens to artistic works, the final solution might reflect the designer intentions and some subjective choices. Second, constant testing of physical artefacts might be more laborious and time-consuming than running and testing a software, although computer simulations can also be used for debugging, e.g. structural behavior. Third, collaborative development demands interested users/volunteers in a specific project. A study conducted by Bonvoisin et al. (2018) indicated that out of 105 OSH projects hosted at *Github*[7], 35 (33 percent) had only one person actively contributing to the edition of Computer-Aided-Design (CAD) files. Although project documentations are fully shared to any user, should it not be considered open because it lacks evidence of collaborative development, especially at early stages of development? Again, the possibility to adapt, modify and optimize open designs still exists. But collaborative development seems to be more like a supportive possibility to open design processes than a mandatory requisite.

There three main elements of an OD project: (i) its design process, (ii) its documentation and the (iii) sharing freedoms. These elements are identified in a wide range of definitions in the literature, e.g. Aitamurto et al. (2015). They contribute to the understanding of openness as a variable, meaning that an OD project can be considered more or less open based on how these elements are articulated.

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[7] Github is an online repository with version control initially developed for software development. As for today, Github is used for developing a wide range of "products" including hardware, music, graphical designs, etc.

2.3.1 Documentation

Let's take a small paperboard box container as an example. In order to cut the box assembling profile, one can either use scissors and rulers or use a laser cutter. In the first case, simple instructions and reference drawings/pictures (in any readable file format) are sufficient to provide the needed information. As for the second case, some digital file formats, e.g. CAD drawing, are required so that the laser cutting process can be performed. Of course, the reasons for choosing between different methods are variable. The idea here, is to illustrate the meaning and purposes of documentation.

Documentation therefore refers to the information needed to build, develop, modify or manufacture an artifact. The type of documentation differs according to the complexity of the object designed or the manufacturing process defined during the design process. Information can be provided as a set of instructions, as source files or both. In general, a set of instructions is sufficient if the artifact is assembled using existing components. However, in higher degrees of openness, information is released in form of editable file formats, e.g., 3D Models, preferably in non-proprietary file formats.

2.3.2 Design Process

Collaborative design processes are well documented in studies on Open Source Software development (MEYER, 2003) and problem solving (AFUAH; TUCCI, 2012). Benefits are often associated to higher innovation rates, increase in knowledge production, faster debugging and improvement rates (RAYMOND, 1999). It doesn't mean that the quantity of stakeholders participating in a design process directly reflects on effectiveness of the community. Examples from OSS development show that in high diverse communities, frustration and conflicts tend to increase (WANG; SHIH; CARROLL, 2015). It is also possible that the initial stages of the design process are developed by an individual who later decides to release his design to the community either for further development or for usage. Enzo Mari's design pieces, for instance, were individually designed and then openly shared. On the other side, the *Open Source Ecology community* collaboratively develops open projects for fifty industrial machines, e.g., 3d-Printer, micro-tractor, bakery oven, etc. (OPEN SOURCE ECOLOGY, [s.d.]). Activities in collaborative development processes can be of different nature. Users might actively collaborate changing the source documentation, e.g. updating design plans and models, reporting bugs, creating derivate works or making part of a forum community. It is not expected therefore that users within a collaborative design process have a same participation level. However, the conditions for that should be pursued if complete openness is desired.

2.3.3 Sharing Freedoms

The adoption of Open licenses clarifies to the user which are the freedoms and restrictions that apply to a specific OD. At the same time, it prevents the misuse of a project and future disputes over intellectual property. Examples of these types of licenses are the MIT License, GPL, CERN Open Hardware License (OHL) and Creative Commons[8]. Some of the licenses are mostly intended for software, some hardware projects have adopted them as an alternative. The Creative Commons current licenses offer a consistent framework for physical artifacts as well as other content, e.g., art works, literature, data etc. (CREATIVE COMMONS, 2017; FJELDSTED et al., 2012). The licenses encompass a full spectrum of freedoms and restrictions, ranging from complete freedom – to use, modify, redistribute and commercialize – to restricting modification, redistribution and commercialization.

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[8] MIT License was developed at the Massachusetts Institute of Technology either for free and proprietary software. GPL was created by Richard Stallman from the FSM and stands for "General Public License". It is considered one of the most permissive licenses. Finally, CERN (European Council for Nuclear Research) has developed an OHL aimed at technology transferring. It is considered the GPL of hardware.

2.3.4 The principles of openness

The elements – documentation, design process and sharing freedoms - are common to any OD project. The characteristics of these elements affect the quality of an OD project, from openness perspective. For that reason, authors indicate a set of general "conditioning factors" which I will refer as principles - the fundamental rules or the essence of an entity or phenomenon. These principles define the goals which any OD project should pursue.

West and O'mahony (2008) are considered the first authors to identify transparency and accessibility as two distinct forms of openness. According to the authors, accessibility defined the extent to which *"external contributors could influence that production.* As for transparency, it refers to the full documentation of a design process which allows users to understand *"what is happening and why"* (WEST; O'MAHONY, 2008). Later, based on the definitions presented, Balka (2011) investigated the structure, i.e. actors, processes and objects, of existing open design projects. Following the preliminary findings, which pointed to selective revealing of appropriate knowledge, the author added to West and O'mahony principles, the term replicability (BALKA, 2011 p.82). Balka introduces the importance of "replicability" as a principle of openness. Her argument is that a design cannot be considered open if the components needed to assemble a product are not available. In other words, a fully replicable designs focus on the use of components that are easy to obtain from external sources or to produce. In this sense, OD should, by principle, guarantee that anyone, professional or amateur, is able to reproduce, optimize and customize such projects. However, it is arguable whether replicability and the other principles have overlapping ends. Transparency, for instance, is also a characteristic of replicable design objects, i.e. in order to be replicable, documentation needs to provide fundamental information.

Table 3 - Open Design Principles

Principles	Definition
Transparency	Refers to the full documentation of a design process in order to allow contributors/users to understand "*what is happening and why*" (West and O'mahony, 2008). The source file is provided without any restriction and no fundamental information is denied.
Accessibility	It also denotes the possibility of users to actively contribute to the development of an Open Design project, from simple suggestions to actual modifications.
Replicability	Refers to the possibility of reproducing a physical artifact using similar settings as the original design. It depends on the availability of components and material.

Principles that contribute to openness in OD processes

2.3.5 General Remarks

The discussions regarding the elements and principles of OD indicate that the idea of pure OD is an abstraction, i.e., full openness is not achievable in practice (BOISSEAU; OMHOVER; BOUCHARD, 2018). Instead, it is a target which can be partially fulfilled depending on how its principles are addressed during the development of an OD project. In fact, recent studies have tried to assess openness in OD projects by having, as a starting point, the principles mentioned in Table 3 (BONVOISIN; MIES, 2018). In Figure 3, I illustrate how the different characteristics of the elements affect openness based on the literature and definitions (CREATIVE COMMONS, 2017; OKFN, 2012).

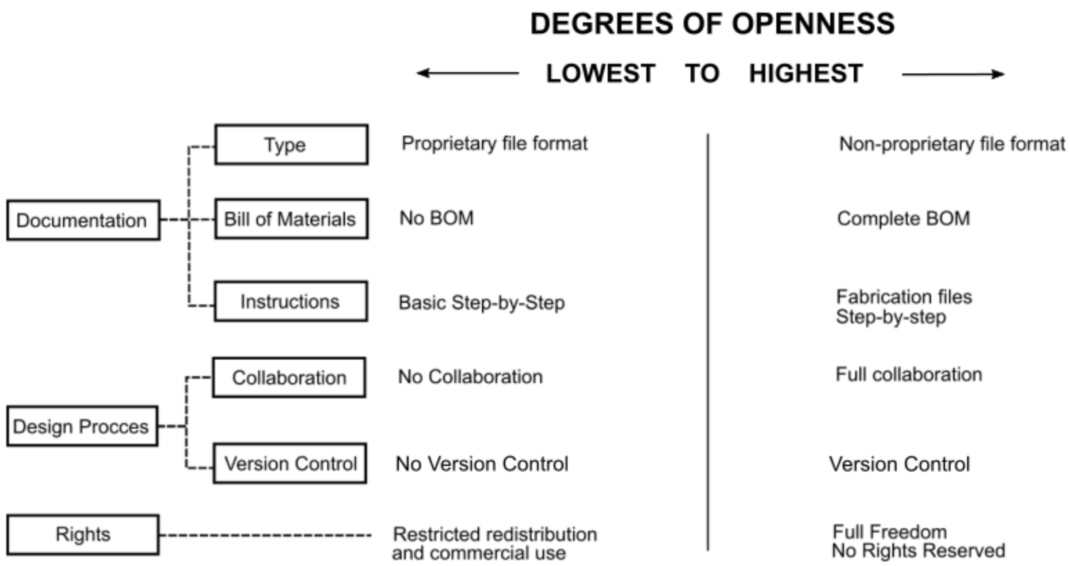

Figure 3 - Openness as a gradual concept according to the documentation, the design process and sharing freedoms. (Source: Developed by the author)

In the previous section, I introduced the historical evolution of the Open concept since the establishment of the Free Software Foundation (FSF). As it was shown, the initial movements forked into new projects, organizations and definitions. The dissatisfaction with the term "Free", its implications to a widespread adoption by companies and its restrictions to some license possibilities resulted in the creation of the term "Open" and The Open Source Initiative (OSI). The idea is that the term open source better reflects the collaborative development model and is more attractive to businesses approaches. However, neither the FSF nor the OSI encourage the developer(s) to release their works into public domain without applying any sort of license. The approach links to Ostrom's proposal of self-regulating small units to govern the knowledge commons (OSTROM, 1990).

There is a valid discussion whether licenses which restrict design modifications and commercial redistribution can be included within the open concept. Critics of such restricting licenses point that it goes against the user freedoms – the basis of the free/open concept – and therefore should not be accepted by the OS communities

(STALLMAN, 2009). Yet, it possibly restricts entrepreneurs to get involved in collaborative development and has a negative impact in the creation of local economic opportunities, especially within the context of poorer communities. On the other hand, there are two main arguments to the adoption of such restrictions. First, examples show it is an alternative which guarantees the designer a compensation for his work (monetary or not) (MONO DESIGN, [s.d.]; OPEN DESK, [s.d.]). Second, it offers a better way to protect the commons, especially in creative works. Different alternatives have been explored by the OSM community. The Creative Commons, for instance, developed the Developing Nations License and the Sampling License. The first, restricted open access to users/companies located in developing countries whilst the second enabled the user to (i) execute/distribute it for non-commercial purposes or (ii) extract samples or mash-up for both commercial and non-commercial ends. Despite the licenses intentions to tackle those issues, they were discontinued because of a lack of interest of the community.

The development of new technologies to support design processes, e.g., Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) systems, and ICTs are basic conditions to the emergence of a solid ecosystem for releasing content and sharing design documentation. The principles of accessibility, transparency and replicability are therefore improved by the existence of solutions, such as collaboration platforms, version controlling instruments, and discussion forums. I highlight, however, some possible limitations to OSH/OD development in comparison OSS. It seems clear that software development in collaborative processes is more likely to success than hardware development. On the one hand, software development demands less infrastructure, e.g. proprietary software/file formats, for collaboration. In addition to that, documentation is usually limited to a set of programming codes. Physical artifacts, on the other hand, deals with a larger set of complexities. There is a wide range of proprietary file formats and software for drawing and modeling. Although it does not affect the quality of the design, it does affect the principles of OD by, for instance, restricting users without specific software to participate in the development process. Lastly, prototyping and debugging processes might demand manufacturing technologies, not always available, to prototype the artifacts, e.g., CNC-mills and 3D-Printers.

Recent studies have explored the benefits of OD to the different stakeholders affected by it, including professionals, users and companies. In next section, I will explore these benefits and introduce some existing cases of OD in the field of architecture and urban design. Some research questions are then developed based on the literature and examples from OD communities.

3 Openness as an alternative...

3.1 ...to the way we design and manufacture

Benefits of OD have been associated to design democratization (BOISSEAU; OMHOVER; BOUCHARD, 2018), citizen empowerment (KOHTALA, 2016), better understanding of user/customer needs (ZHENG, 2009) and distributed manufacturing (DAFERMOS, 2015; LAPLUME; ANZALONE; PEARCE, 2016). Alternative innovation processes (SHAH, 2008; VALLANCE; KIANI; NAYFEH, 2001) have also been discussed and experiences in software development show the potential of OS to foster innovation and to generate new business models and strategies (LERNER; TIROLE, 2003). In the field of tangible goods, a wide variety of businesses have emerged: from supplying assembling kits and special components, calibrating and validating prototypes to providing customization services (PEARCE, 2017; SAEBI; FOSS, 2015). Finally, recent studies have also investigated the potential of OD as a promoter of sustainable consumption and production processes (BONVOISIN, 2016; KOHTALA, 2016).

Scaling-up OD projects – and its benefits consequently - therefore is of great importance to tackle contemporary challenges, especially in developing countries. Examples of OD projects aimed at poorer communities already exist, such as the Jerry Can, Field Ready and OpenBionics. Jerry Can is an OS computer server designed for enabling local production at a low-cost. It uses cheap components (some also OS) and, especially, a plastic container, which influences the project name (Figure 4). Field Ready is an organization aimed at developing design solutions for humanitarian and reconstruction aids. However, it fails on provided source documentation for most of the designs, although some are shared in design hosting platforms (e.g. Thingiverse) as OS models (Figure 5). Designs include components/solutions for water supply, shelters, disability and nutrition. Finally, Openbionics is an OS initiative focused on the development of adaptive, low-cost and modular bionic devices, such as prosthetic hands

(Figure 6). Some of the OD benefits are discussed next and trace the path to explore their potential role in architecture and urban design.

Figure 4 -Jerry Can assembling components. (Source: You and Jerry Can)

Name: Flooring Bricks

Part Number: SS005

Purpose: Shredding waste plastic, melting with aggregate to replace cement in standard flooring bricks.

Material: Plastic

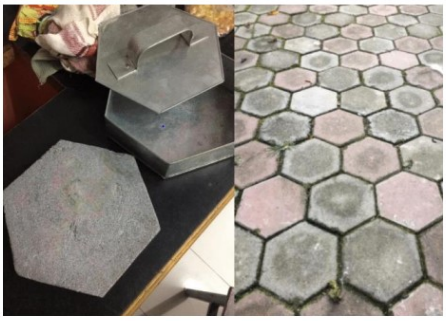

Figure 5 - Example of a solution developed by Ready Field without source documentation. (Source: Field Ready)

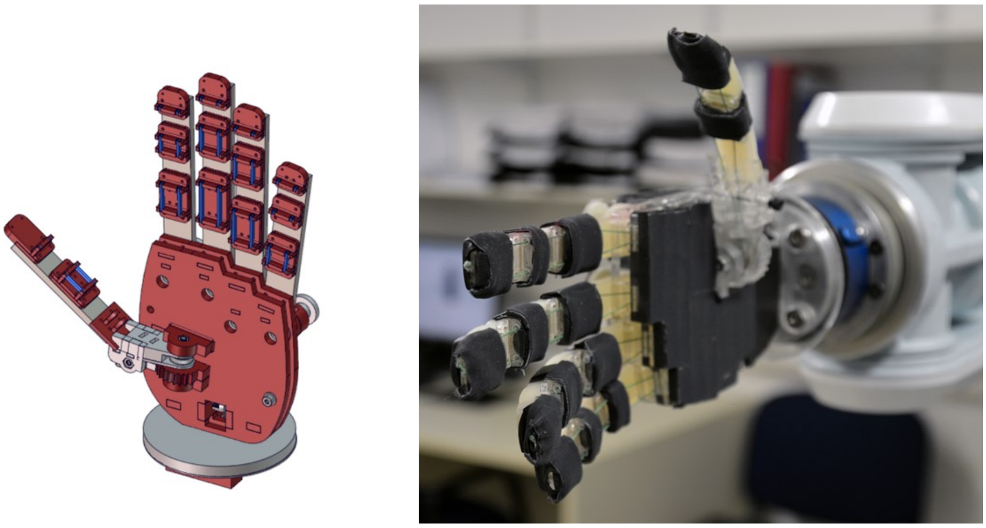

Figure 6 - Prosthetic hand parametric 3d Model (prototype) and prototype (right).
(Source: OpenBionic' Github Page)

3.1.1 Design Democratization and Citizen Empowerment

Design democratization is strongly enhanced because of the development of ICTs, and design digitalization during all the stages of a design process, from sketching to manufacturing. Digital fabrication tools are strongly linked to the maker community. Scholars also define it as a third wave of the Do-It-Yourself (DIY) movement (FOX, 2014). These 'makers' are do-it-yourselfers and high-tech enthusiasts (GERSHENFELD, 2012, p. 48) who usually share design models and experiences in online communities and/or forums. Another contribution of digitalization is that in lessens the need for specialized skills (BOISSEAU; OMHOVER; BOUCHARD, 2018), by enabling users to appropriate from designs shared in online platforms or collaborate in specific design projects.

Some critics of the maker movement, however, question whether it is just another form of unsustainable consumerism and that makers are only producing trendy, un-useful personalized "knick-knacks". Arguments for such assumptions are based on (i) the volume of *bibelot*-related designs in comparison to "relevant" ones in repositories, such as *Instructables, Thingiverse* and *Pinshape* and (ii) their possible higher costs. Although critics are limited to the DIY trend and not the concept of OD, some considerations need to be made. First, a number of OD projects are not hosted in such repositories – given their limitations[9] - which makes it hard to track their existence. A study conducted in 2018 identified at least 242 OS products related to hardware development, e.g. machine tools, robotics etc. (BONVOISIN et al., 2018). Second, although is questionable whether 3d-printing plastic plugs is more cost-effective than buying one in a shop, for example, we cannot affirm the same for products of higher complexity or personalization, e.g. prosthetics. (ZUNIGA et al., 2015). It also does not consider the possibility that specific components are not available in certain locations and therefore local manufacturing is a plausible alternative. In the case of digital fabrication, an increase in makers spaces, such as *Fablabs*, also reduces the need for users to have fabrication equipment (KOSTAKIS et al., 2015).

Design democratization and citizen empowerment are strongly related. However, scholars adopt the term is also adopted in researches on crowd-based innovation, co-creation, collaborative design and citizen participatory processes (GERSHENFELD, 2008; KOHTALA, 2015; PEARCE et al., 2010; SAEBI; FOSS, 2015; TURNER, 2010; VAN DER GRAAF; VEECKMAN, 2014a) . It is important to highlight that I do not include all of these different types of processes within the OD scope. However, the similarities make it possible to understand how open/collaborative processes enable user/citizen empowerment. In crowd-based innovation processes, users or experts with different backgrounds are encouraged to actively participate in product innovation in competition-based processes or voluntarily collaboration (HUTTER et al., 2011; SAEBI; FOSS, 2015).

[9] Limitations of such repositories include, for instance, the lack of a collaborative development process and version control instruments.

It is argued that the outcomes of such collaborative processes directly meet to the needs of the users/customers. Saebi and Foss (2015) illustrate it by using the Made.com case as an example. The furniture retailer company allows users and designers to submit their furniture designs to the website. After being evaluated, the winning design is made available to customers and the original designer is financially compensated. In time, it not only enables customers to participate in decision-making processes but also enables new designers to show and sell their ideas.

The OS/OD debate also exists in urban studies. Jiménez (2014) asks *"What would a city look like if its infrastructures were designed, built, certified, and managed by its residents?"*. His study addresses the adoption of the OS approach to urban design and urban infrastructure and argues the empowering character it has by enabling citizens to actively shape their environments. Bradley (2015) discusses the encouraging aspects of OS Urbanism, Do-it-Yourself (DIY) practices and tactical approaches to spatial professionals to act as "*agents of progressive politics*" in a wider sociopolitical space. Such disruptive approaches result from attempts to optimize locally specific conditions usually not addressed by public or large private investments (EGYEDI; VRANCKEN; UBACHT, 2007; EGYEDI; MEHOS; VREE, 2009).

3.1.2 Distributed Manufacturing

The maker culture is strongly supported by the existence of collaborative workspaces for manufacturing a wide range of artifacts, usually addressed as makerspaces, hackerspaces or Fab Labs. Such spaces give people the access to tools, machines, knowledge-sharing experiences and enable them to design, share and manufacture their own designs (KOHTALA, 2016). The spaces are provided with conventional working tools and other disruptive technologies for digital fabrication, e.g. 3d-printers, laser-cutters and CNC-milling machines.

In his book, Ecology, Andre Gorz (2008, p. 127-130) discusses digital fabrication or rapid prototyping as an alternative to unemployed or underemployed populations. His idea would be to build communal workshops for producing what they and their community needed as a professional activity. The benefits of distributed manufacturing (DM) are also studied by other scholars. Kostakis et al. (2015) refer to a "design global-manufacture local" process which enables new forms of social interactions and its potential to create sustainable business practices. Dafermos (2015) argues that DM is a step towards a post-fossil economy. Others term the DM as "commons-based peer production" (BENKLER; NISSENBAUM, 2006; KOSTAKIS; PAPACHRISTOU, 2014), personal fabrication (MOTA, 2011) or DIY production (BONVOISIN; PRENDEVILLE, 2017). The environmental benefits of DM are often associated to the use of local resources (KOSTAKIS et al., 2015), reduced energy consumption for transportation (LAPLUME; ANZALONE; PEARCE, 2016) and modularity – which favours recycling, reutilization and reassembling processes (BONVOISIN; GALLA; PRENDEVILLE, 2017).

3.1.3 Alternative Innovation processes

In OS software development the open approach is often associated to higher levels of innovation (RAASCH; HERSTATT; BALKA, 2009; VON KROGH; SPAETH, 2007; WANG; SHIH; CARROLL, 2015) because of modularity (NARDUZZO; ROSSI, 2008), constant review of users (identify and fix users) (ELLIOTT; SCACCHI, 2008) and collaborative development (LERNER; TIROLE, 2005). However, an interesting aspect of OS software projects is the "release early, release often" philosophy. Introduced by Raymond (1999), the philosophy indicates that early releases – although might present some significant issues/bugs – are benefited once they are evaluated by multiple users and a new, optimized version is faster developed.

Arduino, an OS electronic platform (microcontroller), enables the development of several types of interactive artefacts, including 3D-printers, temperature controllers, robots, precision scales etc.. The projects are shared in online platforms including the circuit design and programming code. The sharing of the technical information makes it easier to other users to (1) fix possible bugs, (2) copy and adapt the projects to their own needs and (3) share their designs to other users. In other words, there is a continuous development process which makes innovation faster and more reliable. Figure 7 and Figure 8 show two examples of gardening projects shared in online platforms, namely Herb-Box-Eco-System Project and Vertical Hydroponic Farm. The projects use the Arduino controller to automate specific functions, e.g. measuring temperature, humidity, pH levels. As for the Herb-Box-Eco-System, I also illustrate the instructions provided and continuous development process in Figure 9.

Figure 7 - Herb-Box-Eco-System Project. (Souce: Hackster.io)

Figure 8 - Vertical Hydroponic Farm. (Source: Hackster.io)

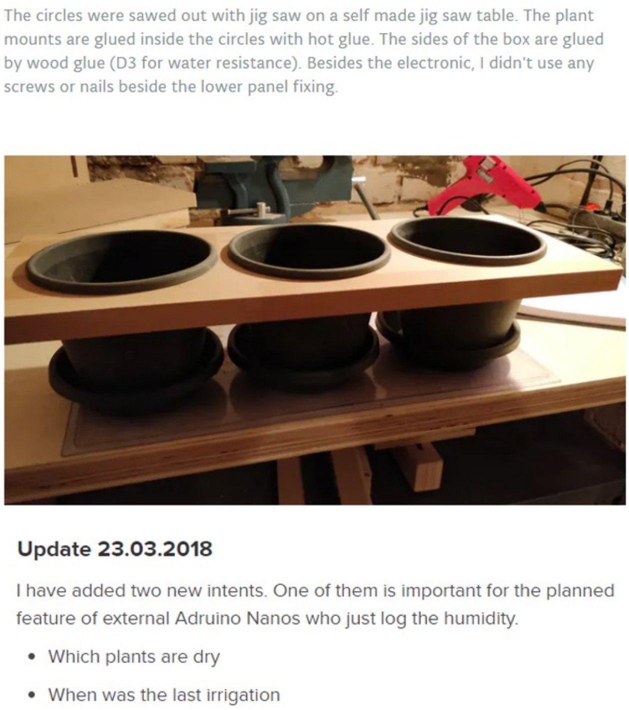

Figure 9 - Example of instructions provided to produce the herb box (top) and updates description (bottom). (Source: Hackstor.io)

3.2 ...to architecture and urban design

As mentioned, OD examples, in form of knowledge sharing, are present long before the emergence of the Open Source Movement (OSM). Current practices in architecture, however, adopt collaboration between professionals and participatory design. To a certain extent, both approaches adopt some of the OD principles. On the one hand, current collaborative processes help architects, urban designers, urban planners, engineers and other professionals to make compatible versions of the same design in order to minimize errors during construction phase and make the decision processes more transparent (BOLAND; LYYTINEN; YOO, 2007; MERSCHBROCK; MUNKVOLD, 2015). These processes are benefited from the development of technologies for drawing, such as Computer-Aided Design, Parametric-Aided Design, Building Information Models (BIM) and other tools/software for collaboration, e.g. NavisWork, Recap, ProjectWise Design Integration and Project Performance Dashboards. On the other hand, participatory design considers all stakeholders – partners, clients, users and citizens – during the design stages as an attempt to meet most of the needs it can. It is important to highlight existing criticisms to participatory processes, especially in urban planning. Current participatory planning practices often fall on a 'pseudo-participation' discourse (MIESSEN, 2010). Community planning is often used by politicians to reduce their responsibilities (TOWNSEND et al., 2010), or it is also used by influent and well-organized groups, sometimes related to private sectors, to impose their interests.

At the same time, OD as a process which "source documentation is made publicly available so that anyone can study, modify, distribute, make, prototype and sell the artifact based on that design", has yet to be broadly explored in the field of Architecture and Urban Design, especially by its professionals. As it evolves, technology becomes more democratic and cheaper. Activists, hackers, individual entrepreneurs or engaged citizens make good use of their computer abilities to spread out useful data, optimize systems, build collaborative networks or develop OS tools and apps. In addition to that, there is a growing number of physical artefacts projects developed under OD processes. The possibilities go from sharing low-cost and rapid-assembly components for building houses (Wikihouse and OpenSource Ecology), furniture fabrication (Made.com and Opendesk) and gardening tools (AKER), to the sharing of architecture projects for social housing (Elemental) and collaborative design (Bricks). However, it is not clear whether all these cases comply with the principles of OD mentioned in Section 2.3.4. Other OS initiatives, not only related to physical artefacts include the OpenStreetMap, a collaborative mapping system and CityOSAIR, a collaborative air monitoring network based on OS metering devices.

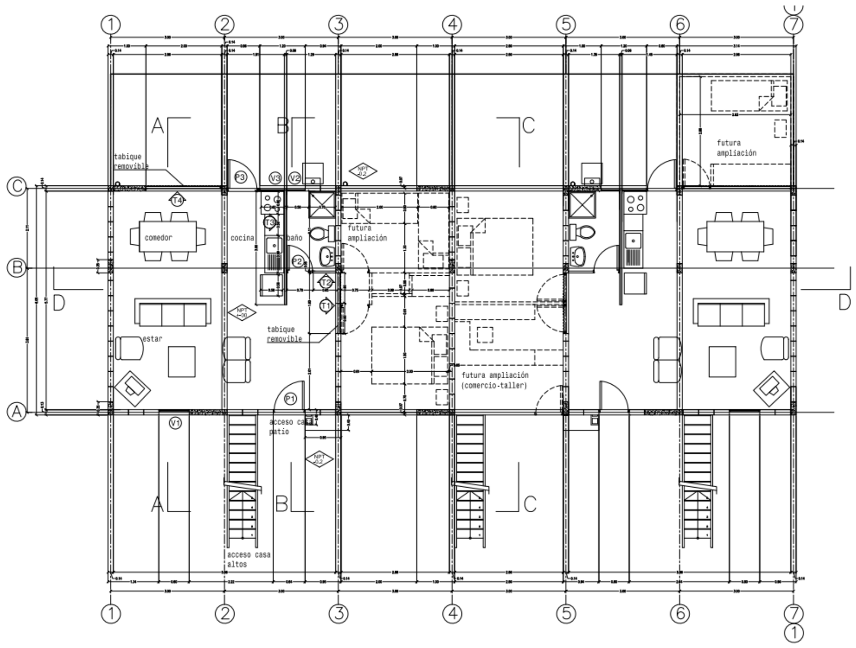

Figure 10 - Example of documentation provided by Elemental for the Quinta Monroy housing project. (CAD file). (Source: Elemental)

Figure 11 shows a building example of the WikiHouse project and Figure 12 shows part of the design documentation distributed by the community. The parametric files are licensed under Mozilla Public Licence 2.0 (MPL), which gives special grants to contributors of the project. The examples illustrate the use of OD in the development of micro-scale building units.

Figure 11 - Wikilab at UFABC (Universidade Federal do ABC. The building design was based on the original's WikiHouse project. (Source: Wikilab)

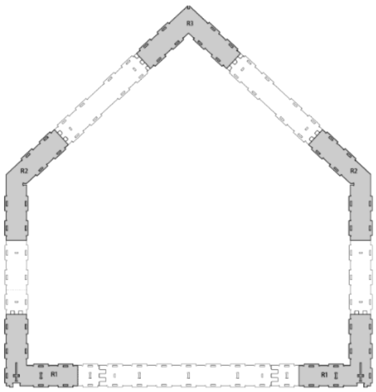

Figure 12 - Structural reinforcers of the building frame (grey). (Source: Wikihouse Github Page)

In this context of shared information and collaborative communities, there is a need to understand the new possibilities of the professional practice. The access to architects and urban designers in developing countries is considerable low. In Brazil, 70 percent of dwellings are self-built (ABIKO; GONÇALVES; CARDOSO, 2003, p. 39) and 85 percent of renovation works are made without professional supervision of architects or engineers (CAU/BR, 2015). Self-building and unsupervised processes are commonly associated to poor quality buildings and negative impacts on the urban environment (PETTANG; TATIETSE, 1998). The lack of design quality of self-built houses might result, for instance, in low environmental comfort quality (KOWALTOWSKI et al., 2005). In addition to that, the urban environment is usually neglected in self-building processes because dwellers tend to focus on improving the private space, and the public sector focuses on basic infrastructure development (MONTEIRO et al., 2009).

Poorer cities also face difficulties to find/hire highly qualified professionals to develop solutions for urban issues. The number of potential clients indicates that the current business model and professional practice is in the wrong direction. The UIA-UNESCO Charter for Architectural Education (UIA/UNESCO, 1996/2011) states that architects should accept the role of "enablers" rather than "providers". Instead of delivering solutions upon customer request, architects should be able to develop tools, protocols, etc., enabling citizens to autonomously act in the built environment. Examples in OD contribute to the argument that it is a viable pathway to this "new" role of architects. Although some limitations still apply for some locations, e.g. the use of digital fabrication processes, I argue for the possibility it represents in future ways of acting in and for the built-environment. It particularly changes the perspective of the professional practice by enabling the architect to contribute to *"the improvement of the quality of life of those who are not accepted as citizens in their full right and who cannot be counted among the architect's usual clients"* (UIA/UNESCO, 1996/2011).

While the urban environment is neglected by the public sector, it is possible to identify self-organizing processes which make an attempt to solve specific local issues. Next, I use two examples to illustrate existing self-organizing processes in situations where infrastructure does not exist or collapsed. The first one is the "Liter of Light" project. It uses plastic bottles, water and bleach to capture and reflect sunlight inside dwellings during day-time. The project originated from an individual initiative who sought to minimize his electricity consumption during a national energy crisis in Brazil, in 2002. Currently, the project has been implemented in several countries by NGOs and two other versions of the original creation have been developed: a portable lantern and a light pole, both based on solar panel and LED lighting systems (LITRO DE LUZ, [s.d.]). The second example refers to an autonomous initiative in the urban realm. In 2016, a group of neighbors decided to build a pedestrian bridge connecting two neighborhoods in Barra Mansa, RJ. The initiative was taken after two decades waiting for the municipality to solve the issue and cost less than 2% of the total that the municipality has previously estimated (LISSARDY, 2016). Although there is no available information regarding the structural stability of the bridge, it is possible to note that the bridge design does not comply with accessibility standards. Figure 13 shows the light pole project implemented by the "Liter of Light" NGO and Figure 14 shows the pedestrian bridge collaboratively built.

Figure 13 - Light Pole – Example of Open Source innovation to light up Public Spaces. (Source: LitrodeLuz)

Figure 14 - Pedestrian bridge built by local residents in 2016. (Source: Folha de São Paulo)

In organization studies, autonomous processes refers to those initiatives that emerge outside the *status quo* of the companies and often derive from new combinations of individual and organizational skills and capabilities (BURGELMAN, 1991). We can adopt this same approach to discuss the urban scale if we consider that citizens can actively change places in order improve it or make it less susceptible to unexpected events.

Again, these autonomous processes already exist, especially in places that lack public investments and/or access to specialized knowledge (TALEN, 2015), and challenge traditional "*assumptions of who and how spaces may be produced*" (GAMEZ; SORENSEN, 2014). Lastly, it is also important to question the technical reliability of such autonomous processes.

The origins of such actions date the 1970's. Talen (2015) describes the work of Karl Linn, a landscape architect who helped communities to develop community spaces and gardens (neighborhood commons) and developed a set of resources and bottom-up strategies to create instant public spaces. Beyond the practice, criticisms of traditional top-down planning exist since the 1960's with the sociological works of Guy Debord, Henri Lefebvre and Michele De Certeau (DOUGLAS, 2014). Debord (1967, p.48), for instance, criticized authoritarian decision-making processes which imposed standardization in urban shaping processes and generated abstract spaces. As for Lefebvre, he criticized the repetition, the artificial and contrived practices in architecture and urban planning, common in modern cities who *"have driven all spontaneity and naturalness from the field, and, in short, that products have vanquished works."* (LEFEBVRE, 1991, p. 74). However, if technology helped standardization processes during the post-modern years, can it now offer new possibilities for social interaction, collaboration and action in the urban realm?

3.2.1 Understanding the process

Recent bottom-up urban transformations have called the attention of scholars, which classified such autonomous processes as Do-it-yourself (DIY) Urbanism (FINN, 2014; TALEN, 2015), DIY Urban Design (DE LANGE; DE WAAL, 2013; DOUGLAS, 2014), Pop-up and tactical urbanism (TALEN, 2015), Open Source Urbanism (BRADLEY, 2015; CORSÍN JIMÉNEZ, 2014), and Inverse Infrastructure (EGYEDI; MEHOS, 2012; HEINO; ANTTIROIKO, 2015). There is no particular consensus regarding the use of the different terms, which seem to be idiosyncrasies, having different meanings to the people and initiatives who generated them. For that reason, I will adopt the term Open Urban Design (OUD) to refer to the spectrum of processes and projects within the urban realm linked to OD which outcomes result in the development of physical artefacts of any nature. These processes and projects have different levels of openness associated to the principles – earlier defined - of transparency, accessibility and replicability. Cases defined as DIY-Urbanism, Opensource Urbanism and Inverse Infrastructures are therefore examples of OUD.

DIY-Urbanism, for instance, can be both a synonym for terms like Guerrilla, Tactical and Pop-up Urbanism (TALEN, 2015) and a broader concept that includes and differentiates these terms as modes of actions (DOUGLAS, 2014; FINN, 2014). Douglas (2014) defines DIY Urban Design as *"small-scale and creative, unauthorized yet intentionally functional and civic-minded contributions or improvements to urban spaces"* and divides it in three categories: guerrilla greening, spontaneous landscaping and aspirational urbanism. As for De Lange and de Waal (2013), DIY Urban Design definition is limited to co-creation and crowd-sourcing processes.

Parallel to the increase of DIY initiatives - these spontaneous actions, with low budget and often temporary physical installations – the Opensource Urbanism (OsU) have been used to define both small-scale interventions in public spaces and true collaborative developed small-scale infrastructures *"designed, built, certified and managed by its residents"* (CORSÍN JIMÉNEZ, 2014). Jimenez points out that OsU projects are developed through networks of expertise and skills that are not locally limited. Such projects are in an eternal "under-development" status – as a reinterpretation of the "release early, release often" philosophy – because of their proliferation nature. It is also interesting to note that his approach to OsU is not necessarily limited to urban equipment, but it extends to artefacts that address urban issues. The "Tetra Cleta", an adapted bicycle's design to function as a market stall or to carry heavier loads, is introduced as an example of OsU. Figure 15 shows part of the assembling instructions of the “Tetra Cleta” shared by the *Inteligencias Colectivas* group. Full documentation (2D plans and 3D model) is also shared in CAD format.

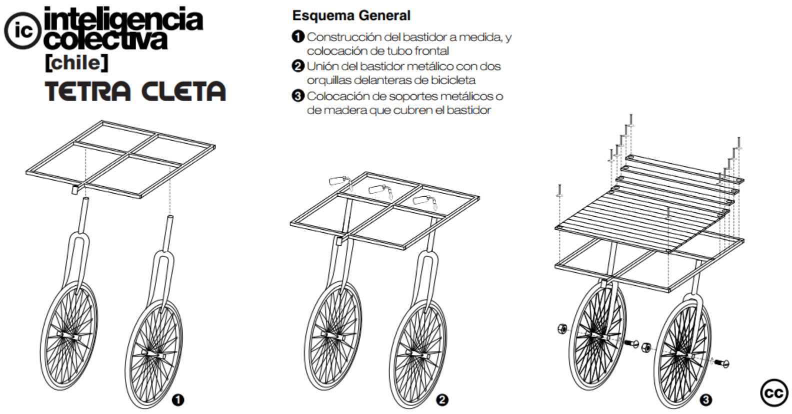

Figure 15 - Isometric perspectives of Tetra Cleta shared by Inteligencia Colective. Designed by: Ivan Lopez Munuera. (Source: Inteligencias Colectivas)

On the same direction of Opensource solutions, “Inverse Infrastructures” is a term coined by Wim G. Vree to describe a category of infrastructures that are user-driven and self-organizing (EGYEDI; MEHOS; VREE, 2009). Here, “Inverse” is related to large-scale centralized infrastructures that are the current model in cities. Four important aspects characterize this type of structure: (i) user-driven development, (ii) self-organizing, (iii) decentralized governance and (iv) bottom-up investments. The examples vary from reaching populations in remote areas with communication technologies (WESTERVELD, 2012) to self-organizing water services (HEINO; ANTTIROIKO, 2015). Inverse infrastructures are also seen as an alternative to deficiencies in traditional public infrastructure and market-based solutions, i.e. in areas where private investments are not economically attractive (*Ibidem*).

These terms indicate that bottom-up approaches have different ways of acting in the urban space. There are two important factors to comment on: the existence of different degrees of informality and complexity. It is important to understand that in OU a wide variety of projects may occur. Community gardens, temporary events, mobile vendors, self-built infrastructures (Figure 14) are examples of different interventions made by users. In these cases, citizen spontaneity plays an important role. Another possibility refers to the relation between professional and citizens in the design process. It encourages those who are not formally trained – but have the skills – to propose solutions, adapt and improve existing *"prototypes"*. As for architects, designers and other professionals they collaborate with technical expertise to develop and share frugal and complex solutions to address common urban issues. The idea of inverse infrastructures, for instance, could benefit from such approach where professionals collaborate and certify that minimum quality/safety requirements are satisfied in bottom-up projects.

To conclude, OUD refers both to the process and the outcomes of OD projects. It is subject to the principles of transparency, accessibility and replicability, and the elements of design documentation, sharing freedoms and design process. The outcomes of OUD are physical artefacts which might (1) directly affect the urban space, as community gardens, or (2) are indirectly related to it but linked to broader urban issues, e.g. residential rainwater harvesting systems.

4 Methodological Framework

4.1 Research Questions

In comparison to OSS, researches in OD are still recent. However, we can find an increasing interest of researchers to understand its ecosystem, its implications and to explore its applications in different sectors. Balka (2011) studied the dynamics of OpenSource, explored the meaning of openness and developed a set of openness principles. Dexter (2007) detailed a methodology for the open development of medical products and highlighted the role of designers as mentors in OD processes. Silver (2011) validated a conceptual framework for an open collaborative system development in the field of biotechnology. Menichinelli (2015) proposed a meta-design approach to improve co-designing processes. Others have focused on digital and distributed manufacturing tools, within the scope of OD, to explore sustainability (KOHTALA, 2016), personalization (SINCLAIR, 2013), the maker movement (NEVES, 2014) and implications to professional practice (DIAS, 2015).

Studies also indicate the possible implications of ICTs and OD to the professional practice of architects and urban designers (CORSÍN JIMÉNEZ, 2014; DE LANGE; DE WAAL, 2013; FINN, 2014; TALEN, 2015), and existing cases, e.g. Wikihouse and Open Source Ecology, illustrate the possibilities of such approach. Several terms have been coined to explore recent practices, e.g. Open Urban Design. Still, little had been investigated in the field of architecture and urban design to (1) explore the viability of OD as an alternative for professionals, (2) understand its limitations to the lay user, (3) evaluate its potential to address sustainability challenges and (4) explore the current practices in remote collaboration.

The aim of this thesis is to investigate OD as a contemporary phenomenon with possible implications for architecture and urban design. To address existing gaps in the literature, I first highlight the need to better understand current practices in OD and potential benefits for design democratization, distributed manufacturing and alternative innovation processes. For that purpose, two initial exploratory Research Questions (RQ1 and RQ2) were developed. These questions were used to build a deeper understanding of OD and its current limitations. The expertise from these studies were adopted to address Research Question 3 (RQ3), which aimed at identifying alternative pathways to improve OD reachability. Finally, Research Question 4 (RQ4) explored collaboration processes and potentialities in OD.

The extensive literature review on OS, OSH and OD, besides current discussions in OUD, enabled me to identify very particular questions which could contribute existing and future studies. These questions are outlined next.

RQ1: How do the different aspects of openness affect artefact manufacturing?

RQ2: How does Open Design relate to sustainable development? What are the current limitations and possible pathways to overcome such limitations?

RQ3: What are the current challenges for replicability in OD and how to overcome them?

RQ4: What is the structure of an OD collaborative community? How and Why users collaborate?

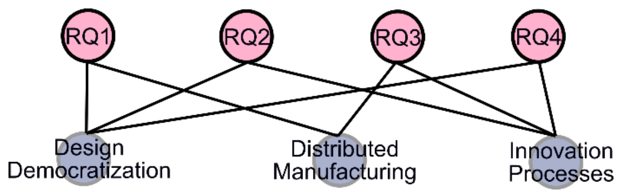

Figure 16 -Research Questions and links to OD

It is important to highlight that these questions have adapted and evolved along with the research development. Next section is dedicated to explain this process and introduce the multi-method approach adopted in this thesis.

4.2 Research Methods and Tools

I adopted a multimethod research design to address the four RQs introduced. Multimethod research is defined as a research which employs *"two or more different methods or styles of research within the same study or research program rather than confining the research to the use of a single method"* (HUNTER; BREWER, 2015, p. 187). Given the exploratory and emerging nature of the research, this approach enables constant evaluation of each stage (question) and the use of the acquired knowledge to address the following stage of the research. A brief description of each RQ is presented next and the complete methods and tools are indicated in each one of the essays.

4.2.1 RQ1

RQ1 is an open-ended question aimed at investigate whether the discourse that OD promotes citizen empowerment and design democratization reflects existing cases. Based on the literature review I adopted the principles of transparency, accessibility and replicability to assess three OD projects. At the moment, modularity was included as a principle given its importance to the design process. The assessment consisted on testing/prototyping selected objects from the cases to check whether they complied or not with the OD principles. Besides the principles, it also discusses the lack of infrastructure as a limiting factor to manufacture OD objects.

4.2.2 RQ2

RQ2 investigates the claims that OD contribute to more sustainable practices in production and consumption. It focusses on the triple-bottom line of sustainability - social inclusiveness, economic viability and environmental responsibility – and the OD principles to assess how OD projects incorporate such values. The Sustainable

Development Goals (SDGs) are adopted to build a set of evaluation criteria. The SDGs constitute a set of 17 major goals and 169 associated targets to "*end poverty, protect the planet and ensure prosperity to all*" in alignment to the social, environmental and economic principles of sustainability. The action-oriented nature of the SDGs enables pragmatic approaches to evaluate sustainability practices (LEVÄNEN et al., 2016). Based on the results for eight selected cases, I draw some future recommendations for improving OD projects.

4.2.3 RQ3

As for RQ3, I adopted the principle of replicability to assess the potential of OD to act over global challenges. The development of the research and a better understanding of the process indicated replicability as the major principle of OD, i.e. the other principles are linked to it. For the purposes of this RQ, I adopted the Residential Rainwater Harvesting Systems (RWHs) as the research object and explored its main components and issues discussed in the literature. The analysis aimed at (i) identifying major limitations communities may face when replicating an object and consequently at (ii) indicating conclusive recommendations for scaling-up OD.

Current limitations of OD and future recommendations were discussed in RQs 1, 2 and 3 enabling me to build a body of knowledge for discussing it from the architecture and urban design perspective.

4.2.4 RQ4

A final study was conducted for an OD community to understand how users/participants collaborate in design/development processes. Existing research already exists within the scope of software development (AALTONEN; SEILER, 2016; WANG; SHIH; CARROLL, 2015; WEST; O'MAHONY, 2008). As for studies in collaboration processes in OD and OSH, they are still necessary to understand the dynamics of such communities. Recent studies have addressed it by using data mining techniques in collaboration platforms, e.g. GitHub (BONVOISIN et al., 2018; MENICHINELLI, 2017) however, such platforms might not reflect the collaborative development. One of the reasons is that communities might use different platforms for communication and design. As for this study, I focused on both data from Github and discussion forums. The approach to RQ4 is both quantitative and qualitative. Using data mining techniques, metadata was used to explore the structure of the community. The selected case is the Open Agriculture Initiative (OpenAg), which mission is to *"create healthier, more engaging, and more inventive future food systems."* (OPEN AGRICULTURE INITIATIVE, 2016). The community uses Github to host the project development files and a community forum is available for making contributions, asking assistance and sharing ideas.

5 Essays

The following essays are presented as they were submitted to the journals/conferences. Therefore, their content may repeat concepts, ideas and definitions already presented in previous sections or essays of this thesis. In order to guide the reader to avoid repetitive information, a grey color is assigned to the parts which present no new information. The reader may skip those parts for easier reading.

5.1 RQ1 – Open Design from Theory to Practice

Introduction

Following the potential of the Open Source (OS) model as a viable alternative for innovation processes and businesses within software communities, other initiatives and definitions were created in the late 1990s and early 2000s. The definition of Open Content, for instance, expanded the limits of Open Source, i.e., the software and its source codes, to anything that is not executable (WILEY, 1998). Different forms of open content are found in academic journals, textbooks, encyclopedias, medias and data. The Wikimedia, founded in 2003, is a prominent example of open content. It supports the different wikimedia free knowledge websites, such as the Wikipedia and the Wikimedia Commons. In 1998, an Open Hardware Certification Program was launched and, in 1999 the Open Design Foundation (ODF) was founded (VALLANCE; KIANI; NAYFEH, 2001). The possibility of applying the OS model to the development of hardware components, physical products or tangible goods called the attention of researchers, enthusiasts and practitioners from other sectors (RAASCH; HERSTATT; BALKA, 2009). Hippel and Krogh (2003) illustrate it by comparing the freely reveal of CAD designs to the freely reveal of software code. Other examples include the clothing, biotechnology and pharmaceuticals industries (LAKHANI; PANETTA, 2007).

Other terms have been created and used to describe the forms that people and communities collaborate in the development of specific projects, products, software and how the knowledge collectively created is shared. The use of different terms can be fuzzy and is mainly limited to the differences between the industry sectors to which they refer. Open Data, Free/Libre Open Source Software, Open knowledge, Open research and Open manufacturing are examples of terms linked to the OS definition but limited to specific objects. In this study, we opted to use the term Open Design as it reflects both the openness philosophy of collaborative creation and content sharing, and the development of tangible goods as a design process.

Open Design: Principles and Definitions

Open Design examples had been present long before the emergence of the Open Source Movement (OSM). The sharing of technical information between companies was an important factor for the technological innovation processes seen during the 18th and 19th centuries. The seminal work of Alexander, Ishikawa and Silverstein in the book "A Pattern Language" (1977) introduced a set of architectural and urban solutions for common issues faced not only by professionals but, especially, by ordinary people. The pattern's concept resulted in derivative works in other fields, such as Computer Science and Software Development (AVGERIOU et al., 2003; BECK et al., 1995; GAMMA et al., 1993). Works in furniture design took place in the early 1970s. The book "*Autoprogettazione?"*, by Enzo Mari (1974) was a collection of simple furniture design published as a critical positioning to industrial production.

Currently, the definition of Open Design (OD) is also subject to different approaches amongst scholars, communities and companies. The Open Knowledge Foundation (OKFN 2012) definition focuses on the publicity given to the source documentation of any artefact design in order for it to be used for any purpose by anyone. The definition also differentiates the levels of openness, considering the documentation format and the design processes. Raasch, Herstatt, and Balka (2009) explore the revealing of information as an intention to achieve collaborative development for either market or non-market purposes. Katz (2011) adopts the FSM philosophy and highlights the importance of the freedom to use, change, study and make derivative works from the original design. Finally, Boisseau, Omhover, and Bouchard (2018) propose, after a state-of-the-art review, that OD requires both the process and the sources to be open. However, we consider the documentation as the single non-variable component of such definition. In other words, any OD project needs to offer the required information, in any readable format, so that it can be used, replicated, modified and redistributed by anyone. An open process contributes to openness; however, it is not mandatory precondition as long as the sources are publicly shared. Indeed, considering pure OD as an abstraction (BOISSEAU; OMHOVER; BOUCHARD, 2018), this issue has already been addressed in studies and propositions which consider the different levels of openness based on different conditions.

Openness principles for developing countries

The Open Knowledge Foundation (2012) identifies the different levels of openness: (i) at the process of design, from non-collaborative to fully collaborative; (ii) at the format of the shared documentation format, from making it available on the web in any format to using only non-proprietary formats; and, (iii) at the license type, from publishing into public domain to maintaining the original author's rights. West and O'mahony (2008) define transparency and accessibility as two distinct forms of openness. Balka (2011) discusses the importance of "Replicability" as an aspect of openness. Although intrinsic to the OD definition, Balka's proposition extends the limits of the documentation to the availability of components and possibility of obtaining them. In this sense, a fully replicable design should have no barriers to its reproduction, be it the lack of information provided or the need for specialized knowledge. What seems important to OD is the possibility for anyone, professional or amateur, to reproduce, optimize and customize such projects using the lesser possible number of proprietary tools and without any hidden data behind the "open" documentation.

The three above-mentioned aspects: transparency, accessibility and replicability are not only complementary to the OD definition but essential principles to its application, especially within the developing countries context. Most of the OD benefits are linked to its possibility of providing democratization of the design process (KWON; LEE, 2017; VON HIPPEL, 2005, p. 124), faster and better innovation processes (SHAH, 2005; VALLANCE; KIANI; NAYFEH, 2001) and citizen empowerment (NASCIMENTO, 2014). In addition, OD is also seen as a promoter for sustainable consumption and production (KOHTALA, 2015) considering especially the environmental aspects of it. Despite this understanding, little attention is given to OD potential to promote sustainability in developing countries.

Access to technologies, materials and tools are, sometimes, limited due to the need for high investments in machinery or simply due to their inexistence at the local level. This is especially true for developing countries. The sharing of open designs to build digital modeling and fabrication tools, for instance, has no practical result if the resources to build it are limited. In the developing context, Openness assumes a different condition. An OD project developed for 3d printers or CNC-mills depends on the existence of such tools, the cost of access to them and material availability. Is it still open if there is no way to replicate it? Clearly, OD is not intended to solve local issues on access to technology, although the Fablabs and Makerspaces are presented as viable alternatives (HYYSALO et al., 2014; NASCIMENTO, 2014).

The replication of a design itself is not sufficient if it cannot be modified and adapted for a different context. We argue that Modularity turns the modification of a design that is easier for users. In fact, the concept of modularization is already considered a driver for Mass Customization, Personalization and Co-creation (NIELSEN et al., 2011), problem solving (AFUAH; TUCCI, 2012) and to OD (BONVOISIN, 2016). We understand that modularity decreases the need for combined skills and knowledge. It contributes to collaborative processes by enabling the user/contributor to focus on very specific aspects of the design, usually on what he is most familiar with. Therefore, it is an important principle of openness if modification of OD projects is envisioned.

In this study, we propose to empirically study the degree of openness of three OD projects, in a practice-based approach. The above-mentioned principles, accessibility, transparency, replicability and modularity were considered to structure our analytical framework (Table 4). However, the core of the research is based on the personal experience of locally manufacturing such projects. The analysis considered the different steps of testing an OD project, from downloading the documentation files to assembling and testing the prototype.

Table 4 - Four principles for openness

OD Principles	Definition
Transparency	Refers to the full documentation of a design process in order to allow contributors/users to understand *"what is happening and why" (West and O'mahony 2008)*. The source file is provided without any restriction and no fundamental information is denied.
Accessibility	Refers to the easiness of access to the source file, especially in non-proprietary formats. It also denotes the possibility of users to actively contribute to the development of an Open Design project, from simple suggestions to actual modifications.
Replicability	Refers to the possibility of reproducing a physical artefact using similar settings as the original design. It depends on local availability of components and material.
Modularity	Refers to the possibility of a design to be separated in modules with clearly defined interfaces. It allows contributors to focus on specific issues, commonly related to their expertise, and facilitates design adjustments for application in other contexts.

Data and Methods: Open Design Criteria

We conducted a literature review on OD. We applied the search term "Open Design AND Definition" to the Scopus, Web of Science and ScienceDirect databases and limited the results to articles produced after 2000. The search returned 227 articles which were filtered considering their relevance to the object of this study, i.e., if they were related to the concept of open design and the development of physical artefacts. Finally, 47 articles were found appropriate to the next stage.

The analysis consisted on identifying the different ways scholars address Open Design, its definition and requirements. In addition to articles, we collected existing definitions from OD communities and manifestos. Finally, we structured four initial principles for evaluating openness in a developing country context. The principles were based on the literature review and consistent to our methodological approach.

Selection of Cases

For purposes of this study, we recognized the need to understand the Open Design applicability within the context of a developing country. The selection of cases consisted of a four-round search. First, we looked for existing projects, communities and companies that promote open design. In order to identify the current stage of the open design community, we opted to explore the web. Second, because of the thesis focus on architecture and urban design, we aimed at exploring artefacts that are, somehow, linked to the built environment. At this moment, the examples found were both related to vernacular techniques and technology. The third round consisted on limiting the search to examples that are linked to a specific process of digital fabrication. At last, we defined three different scales to select the artefacts: The component scale, the activity scale and the system scale.

The component scale refers to any element that cooperates or works together with other elements to form a system. In this sense, a window, a door or a roof constitute a system and a wood frame, a lock and a tile are some of the components of these systems.

The activity/function scale refers to a component or system that has a direct function or permits an activity to be performed. At this scale, the user is the focus of the function or activity. A window function, for example, is to provide natural lighting and ventilation. A chair, at the same time, allows the performance of daily activities.

The system/organizational scale consists on the scale where general and broader functions of a building are performed. At this scale, the user is indirectly connected to the function, although benefiting from it. The enclosure of a building, for example, separates the exterior from the interior of a building.

Finally, we selected three cases that represented each scale and had no apparent limitations in terms of costs and available technology. The cases are briefly introduced next. Table 5 introduces existing examples of OD related to the built environment classified according to the different scales proposed. It is important to note that, at this moment, we did not evaluate the openness of each case but relied on the information presented by the companies, communities and designers.

Table 5 - Open Design Cases

Cases	Scale			Description
	Component	Activity	System	
OpenDesk		**X**		**Furniture Designs**
Faircap	**X**			**Attachable filter for water bottles**
Open Source Ecol-ogy	X	X	X	Industrial Machines for building a small and sustainable civilization
Aker	X	X		Gardening kits Designs
Elemental			X	Public Housing Projects
Open structures	X	X		Modular components for furniture design
Bricksource			**X**	**Parametric brickwork patterns**
Instructables	X	X	X	Repository for sharing ideas, projects, source files and instructions
Paperhouse			X	Housing projects with flexible construction systems
Thingiverse	X			Repository for sharing projects, source files and instructions for 3D printing
OpenHardware	X			Repository for electronic projects. Includes temperature, lighting and humidity sensors, and controllers
Openmotics	X		X	Modules for Home automation
Wikihouse	X		X	Construction components for a modular housing unity

FairCap

Faircap is an Open Source design project aimed at developing a one-dollar ($1) water filter using technologies that allow collaboration, co-creation and local manufacturing. The project started in 2015 and was limited to filtering chemicals using activated carbon as a filter. Currently, the project evolved to the development of a bacteria filter and the first working prototypes have been produced. The documentation uses .STL files for the 3d-printed components of the filter and general instructions for the activated carbon production. Although the project aims at building filters attachable to water bottles, we see the opportunity to explore it in Rainwater Harvesting Systems.

OpenDesk

OpenDesk is a London based company which distributes furniture designs under Creative Commons license, mainly under non-commercial restrictions. The designs are distributed to end-users as a DIY digital fabrication file or to local manufacturers, which produce them commercially. The documentation uses .DXF files for generating CNC-Routing paths and .PDF files with general instructions.

BrickSource

Bricksource consists of an open-source database of parametric brickwork developed by the architectural firm Sstudiomm, located in Iran. Different weaving patterns of walls are available to architects or any other user to download, produce the stencils, and make the brickwork. The documentation uses Rhino and Grasshopper files for the parametric design, i.e., the development of patterns, .XLS files for the bricks angles which compose the pattern, and instructions to assemble the stencils for on-site work.

Evaluation Process

We adopted a practice-based research approach to evaluate the OD applicability. The evaluation proceeded in three stages. First, we selected and studied the cases in order to understand which fabrication tools, processes and softwares we would need to test the designs. From this first contact, a pre-qualitative analysis was made. We attributed the values "-" for negative, "0" for neutral or unclear and "+" for a positive indication of one of each principle above-introduced (Table 6). Second, we proceeded on the experimentation of OD examples and reflection on the process, using the first-stage findings as a guideline. This is the core of this study and is discussed next. Third, the findings of previous stages were presented and discussed with other researchers.

Table 6 - Cases selected and openness principles

Case/Indicator	TR	AC	RE	MO	First Impressions
Faircap	+	+	+	-	It shows interest on developing an Open Source solution for addressing water accessibility issues in poorer countries. The project is based on collaborative creation.
Open Desk	-	-	+	+	It is a business-oriented example of Open Design. It hosts its own files and the designs are apparently well-documented for a DIY approach.
Bricksource	+	-	-	+	Developed in a form of manifesto and distributed as a work-in-progress base. The parametric approach should increase the modularity of its design.

Pre-qualitative analysis for each case based on our first impressions considering the primary information obtained at each project's webpage. (TR) Transparency, (AC) Accessibility, (RE) Replicability and (MO) Modularity.

The practice-based research assumes that the creative process is capable of generating research outputs and/or knowledge (SMITH; DEAN, 2009) while also revealing the *"philosophical, social and cultural contexts"* for the application of such outcomes (BARRETT; BOLT, 2014, p.2). At the same time, the methodology pays special attention to the self, i.e., the researcher individuality during the creative process and his research. From this perspective, the creation of an artefact is considered to be the result of the individual process. On the other hand, we assumed the possibility that open and collaborative processes are also capable of offering the same research knowledge and outputs.

The approach consisted on assessing part of the complex process involved in open design, the prototyping and modifying such designs. For that purpose, we developed a guiding question: What knowledge can be revealed by testing and modifying Open Design projects? The three cases selected above were adapted and tested using digital fabrication tools. We opted for a narrative approach to describe the personal impressions in a detailed way, considering not only the practical experience but also the technical constraints, e.g., material type, costs and availability.

Analysis and Findings

For evaluating whether the OD projects are applicable to a developing country context, we explored all stages of making an artefact. In developing countries, like in Brazil, access to technological tools need to be considered when opting for a Do-it-yourself approach based on OD. The costs associated to the access of the tools might be a hindrance and make it disadvantageous if compared to standard industrialized products, although we are not comparing the quality of such artefacts.

For all cases, there is a description of each stage of the making process. It consisted of: (i) obtaining the source files and instructions, (ii) identifying the needed materials and tools, (iii) adapting the designs to our local constraints and (iv) prototyping the models. The four principles of OD supported our analysis during the experimentation process. Next, we present the findings of our experimentation and a summary of the findings is presented in Table 7.

Table 7 - Summary of findings

Case/ Indicator	TR	AC	RE	MO	Summary
Faircap	-	-	+	-	• Source files are not available for download at the host page. • Source files available in open file format. • Lack of information regarding the development of the projects. • The model dimensions are suited for European Standards. • Modularity would enhance its potential for application in different contexts.
Open Desk	-	-	+	+	• Source files are available for download in proprietary file formats. • Missing information for design production and assembling (although most information is provided). • Non-commercial licenses restrictions. • Modular approach facilitates minor changes in design. • Closed process of design.
Bricksource	+	-	+	+	• Source files are available for download in proprietary file formats. • Graphical Programming modification is limited to the use of proprietary software. • All needed information is provided despite the design complexity. • Documentation consists on 3D Model, Graphical Algorithm and assembling instructions. • Parametric approach increases modularity.

(TR) Transparency, (AC) Accessibility, (RE) Replicability and (MO) Modularity.

Faircap

Presented as an Open Source project for social innovation, we expected the source files, documentation and design process to be easily accessible. However, the official page of the project has no direct access the source files except for a section calling for collaboration. It redirects the user to an online platform for collaborative projects. We were neither able to register nor to access the collaboration page of the project. It was not clear if the project has ended or if the collaborative process failed.

We did find the source files in a different platform, namely *Instructables*. They date to the year 2015, and it appears that they are the first release of the *Faircap* project. The 3d files (.STL) are accompanying a set of instructions, including instructions to produce activated carbon. However, no specifications for 3d printing is given. The 3d models were set for 5-8-liter water container caps. The .STL files is the standard file format used for 3d-printing and it is readable in many Open Source and proprietary (PR) softwares, such as FreeCad(OS), Blender™ (OS), Rhinoceros®(PR) and AutoCad®(PR). We opened the files in all four softwares without any issues and limited our editing to Rhinoceros®. For generating the G-Code and printing the model we used the Repetier-Host application.

After the first tests, we remodeled the thread geometry for better adjustment to a 5-liter commercial water bottle using local dimension standards (Figure 17). Also, because of the lack of information in the printing setup we had to run a few tests with different printing settings before achieving a desirable result. The adjustments for the printing are provided in Table 8. We are aware of the limitations of such solution for biological treatment. However, the instructions show how to produce activated carbon for chemical treatment. The development of an effective biological filter was one of the original aims of the *Faircap* project.

Lastly, we decided to adapt the design for fitting a water pipe of 3/4" inches (Figure 18). We made significant changes to the original design but kept the concept of an attachable component with activated carbon filtering system. We noticed the design potential to function as filter for Rainwater Harvesting Systems (RWHS), at least to filter small particles and chemicals (Figure 18 - 3D-Printed Filters Capsules (Without Activated Carbon).). Studies in RWHS highlight contamination as a main issue to enable a broader adoption of the system in poorer communities (ARKU et al., 2015; BURT; KEIRU, 2009; MWENGE KAHINDA; TAIGBENU; BOROTO, 2007).

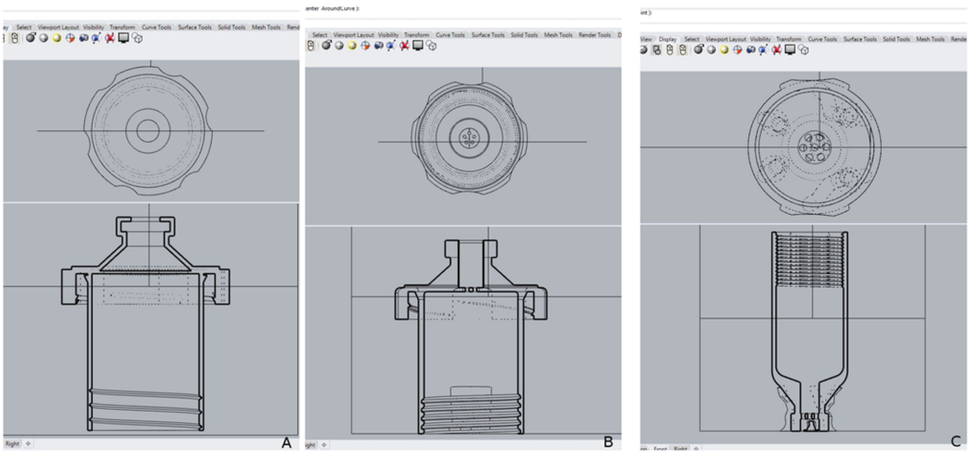

Figure 17 - Faircap original design and derivatives.

(A) Top-view and section of original FairCap model, (B) Top-view and section of adapted thread geometry, (C) Top-view and section of proposed filter for 3/4"pipes to be used in Rainwater Harvesting Systems. (Source: Developed by the author)

Figure 18 - 3D-Printed Filters Capsules (Without Activated Carbon).

(A) The original design (left) and adapted versions. (B) the adapted versions attached to a 5-liter water bottle and to a 3/4" pipe thread connection. (C) Detail. (D) adapted version attached to a faucet with male threaded end. (Source: Author's personal archive)

Table 8 - 3D Printing Setup

3D Printing Setup	
Material	PLA 3mm
Layer Height	3mm
Fill Density	10%
Fill Pattern	Rectilinear
Support Material	Yes
Maximum Speed for Print Moves	45mm/s (Infill)
Printing Time	3:10h for original filter 1:20h for adapted filter (3/4" pipe) 1:17h for filter cap

Basic setup used for 3D printing the .STL files and time spent for each model.

OpenDesk

Most of Opendesk furniture designs are licensed under attribution and noncommercial terms (CC-BY-NC). Others are simply licensed under attribution restrictions (CC-BY). Noncommercial licenses are questionable considering OD definition within communities. In the academia, there is no consensus regarding such aspects. Some scholars adopt the freedom philosophy while others understand the need for noncommercial licenses as a way to maintain the economic viability of a company.

We chose the "Lean Cafe Table" design as our experimentation case. The design is shared in .DXF (Drawing Exchange Format), which is a proprietary file format developed by Autodesk®. The file format was designed to allow data interoperability between other programs. .DXF files can be opened and modified in Open Source softwares, such as FreeCAD, although it requires an extension to be installed. Therefore, the source files are easy to obtain and require no specific software to work it, which increases the aspects of accessibility.

The files were opened both in Autocad® Software and FreeCAD. However, FreeCAD failed on importing the text guidelines. The information provided by the drawing consists of: (i) the type and depth of each cutting, given in the different layers, (ii) the recommended drill bit and, (iii) type of material. It misses on providing the material thickness specification, although there is a field for it (Figure 19).

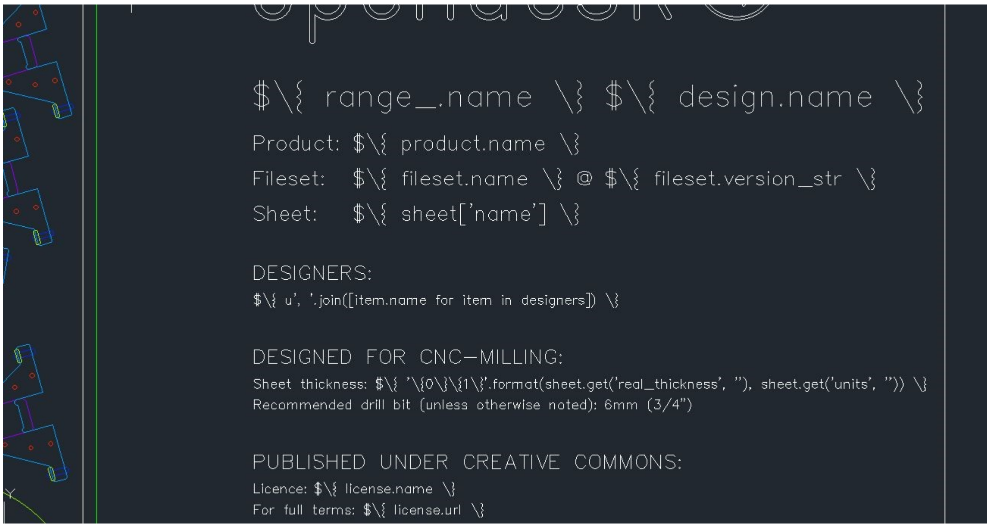

Figure 19 - Information available on OpenDesk source file.

.DXF Files contained fields with missing information for CNC-Routing. (Source: Developed by the author)

We adapted the design for a different material thickness and had to consider the transportation limitations for the sheet size, which required some time and study to understand how joints would be affected and what constraints were connected to each other. The files were saved in .EPS format and opened in Engravelab® for generating de G-Code. The generation of the G-Code was the most problematic part of the process. A ll the lines of a perimeter need to be connected before creating the tool path. The corners and curved lines presented many issues and had to be solved manually. Many of the lines of a perimeter had to be drawn again. Three tests were run before the adjustment of all specifications for the final piece. The specifications, the time spent and the total cost is presented in Table 9 - CNC-Router Setup. We included the standard amount charged per hour for using the CNC-Router machine. Figure 20 shows the process of CNC-Routing and assembling the table parts.

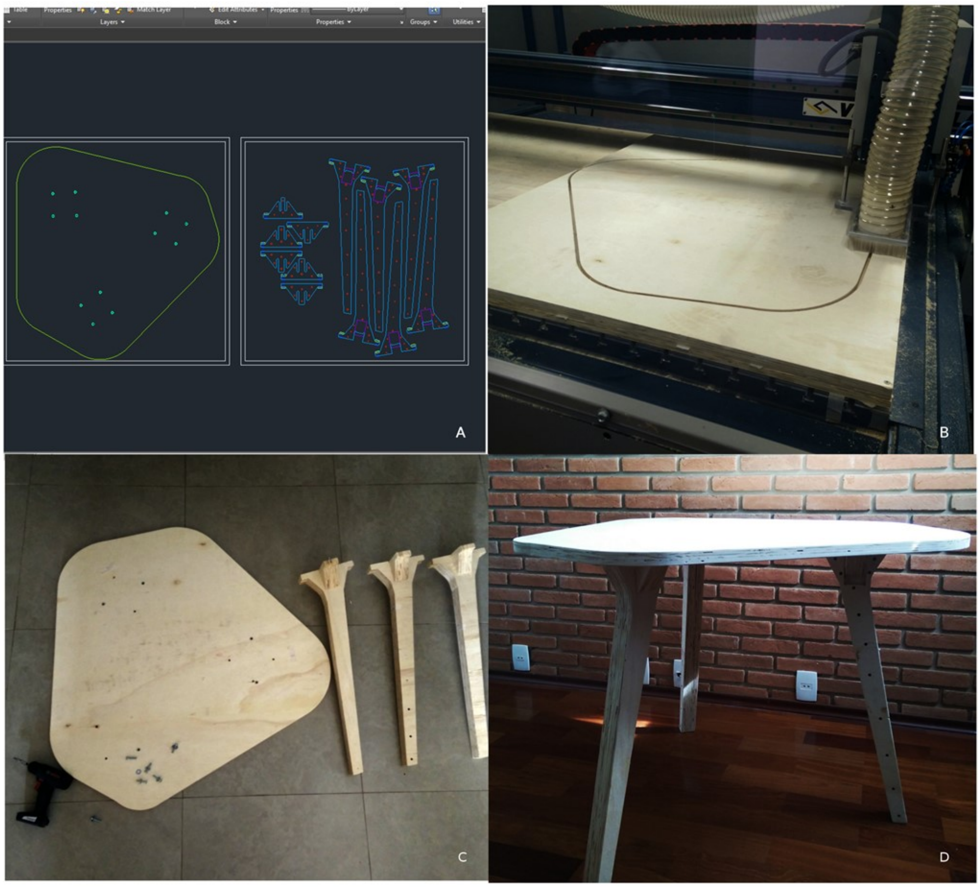

Figure 20 - The process of producing the Lean Cafe Table (CC-BY-NC), designed by David Steiner and Joni Steiner. The Source files were adapted to facilitate transportation and to fit the CNC-Router dimensions. We also added threads for better fixing the table legs. (Source: Author's personal archive)

It is important to highlight that the Lean Cafe Table is also available to be purchased directly at OpenDesk. The business model is based on decentralized production. It means that local manufacturers are enabled by the company to explore the designs commercially. In this case, percentages of the product are distributed between the company, the original designers and the manufacturer. The final price, however, is considerable high if compared to standard products and even if producing in a DIY approach.

Table 9 - CNC-Router Setup

CNC-Router Setup	
Plywood thickness	20mm
End Mill	8mm Down Cut
Depth of Cut	6mm
Cutting Speed (RPM)	12.000
Time Spent	2 hours (adjustment of source files and Routing setup) 2,5 hours (CNC-Routing process)
Fees	$16/hour*
Material Costs	$40

Basic setup used for CNC-routing, time spent and estimated costs. *Considering an USD/BRL exchange rate of 1/3,50

Bricksource

Bricksource was launched as an Open Source manifesto in the form of a construction method available to anyone to use it. It celebrates the use of OS tools and DIY processes by architects and encourages them to explore new types of professional relations, e.g., adopting collaborative processes.

Documentation files are available in different formats, which are used for different purposes. First, the .3dm files have the geometry to be applied by the parametric definition. There are several geometries available for download, although the user is able to design a geometry himself. Second, the .GH file is the parametric setting. Briefly, it transforms the .3DM geometries into a set of layers containing the rotated bricks. It is also possible to export the rotation angle to a .XLS file. Last, the .XLS is a table containing the rotation angles of each brick for each row. These can be used by users to produce the stencils, i.e. the guidance for bricklaying. .3DM and .XLS files can be opened in OS software, such as Blender™ and LibreOffice®, respectively. .GH is a file format used in Grasshopper™, a graphical algorithm editor integrated with Rhinoceros®. Therefore, the modification of the parametric settings and the original geometry is limited to the use of Rhinoceros®. Figure 21 illustrates the stencil generation process.

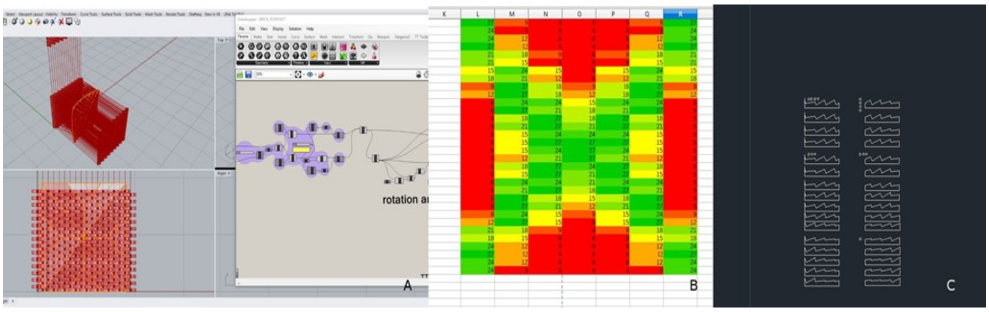

Figure 21 - Stencil Generation Process. (A)The original surface was modified to a narrower version. (B) The rotation angles generated in Grasshopper were exported to a .XLS file. (C) The angles were used to draw the stencils. (Source: Developed by the author)

The process of testing the design consisted on the following steps.

- We used the original X geometry and adapted it into narrower version.
- The parametric settings were adjusted to the new wall length and few changes were made to the brick rotation angles.
- The rotation angles were exported in .XLS format and used to draw the stencil parts in Autocad® software.
- The parts were CNC-Milled and used for bricklaying.

The parametric settings of the .GH are difficult for a first-time user. They require some comprehension of programming concepts and 3D modeling. Although Grasshopper™ is familiar to us, we had to reserve some time to understand the whole parametric setting before being able to adjust it. It is important that the few instructions given inside the .GH file, provide important information regarding the parametric settings. However, the instructions for drawing and making the stencils have no logical sequence.

After exporting the rotation angles to .XLS, we used the angles to draw the stencils in Autocad® software and CNC-milled in 8mm thirty-four plywood boards, two boards for each row. We laid the bricks using the stencils and after reaching the seventeenth row the stencil orders were reversed. We opted to lay the bricks in a way they could be easily removed for other tests. The process is registered in Figure 22.

Figure 22 - Stencils fabrication and lay bricking process. The stencils were cut in a CNC-router machine (A) in 32 different pieces (B). Each row was composed of 2 stencils parts which were used to guide the lay bricking process (C & D). (Source: Author's personal archive)

Bricksource is limited to the development of brick patterns, which is used in facade personalization. Although simple, at-first-glance, personalization is an important feature in buildings, especially in self-construction processes. The low-cost stencils are reusable and several material alternatives can be proposed, from cardboards to metal.

Because of the complexity involved, the architect (or other professional) plays an important role by enabling the use of such tools. Finally, we also envision the possibilities of further exploration of the .GH scripts. to generate passive lighting and ventilation solutions, for instance.

Discussion

This study has empirically explored the applicability of Open Design. For this purpose, we studied, reproduced and/or adapted three OD projects. The whole process was taken into account, from obtaining the source files to producing the designs.

Our literature review showed that there is no definitive definition for Open Design. Meanwhile, openness is defined as a gradual concept to address the different OD projects, considering the documentation format, the design processes and the license attribution. In this study, it was not our aim to define a set of parameters to define openness. Instead, we aimed at exploring the specificities that make each OD project more or less open from the user perspective. Next, we discuss our practical impressions and findings based on four principles: Transparency, accessibility, replicability and modularity.

Transparency was a problematic aspect of the OD cases for three specific reasons. First, the direct production of the artefacts is hampered by the lack of essential information, e.g., printer settings (for Faircap) and material specification (Open Desk). Second, none of the cases encouraged collaborative creation. The existence of any type of environment for sharing ideas is as a fundamental for collaborative creation (MURDOCK, 2004; SAWHNEY; VERONA; PRANDELLI, 2005; VON HIPPEL; KROGH, 2003). Even the Faircap project, which has a pro-collaboration discourse, did not offer a working platform for sharing ideas and improvements documentation. We understand that some projects fail to keep being developed for different reasons (AFUAH; TUCCI, 2012; LERNER; TIROLE, 2001). In this case, complete documentation creates a starting point so that it can be further developed in the future by anyone. Lastly, we highlight that commercial exploration of an OD artefact possibly restricts information distribution. In Open Desk, for instance, the designs are selected by the company and developed in a closed process.

Despite the easy access to the available source files, their dependence on proprietary software deserves attention. Although some OS software are capable of importing different file formats, we experienced import errors when importing the Cafe Lean Table files (.DXF) to Freecad. Regarding Bricksource, it was possible to open the patterns examples (.XLS) in LibreOffice. However, the definition files, i.e., the parametric programming, was fully dependent on Rhinoceros and Grasshopper. In this scenario, the existence of fully compatible file formats and Open Source CAD/3D modeling software, is an important factor to address accessibility.

From the replicability perspective, there is little to add besides the restriction caused by the lack of information. After solving this issue, the designs were quite simple to be replicated. However, few adjustments had to be made for the material available. The plywood thickness for the Cafe Lean Table changed from 24mm to 20mm, because of its availability. The bricks used for the Bricksource project are also different from the original specifications.

Lastly, modularity was important for the three cases we tested. First, OpenDesk designs are set to be assembled using specific joints according to different functions. In our case, the adjustments we made regarding the table top size and the plywood thickness did not affect much of the design because of modularization. Few adjustments had to be made at the joints. In opposite direction, the lack of modularity demanded extra work for adjusting the Faircap model to local standards. A modular approach could facilitate such adjustment for different contexts. In collaborative processes, modularity is fundamental because it allows contributors to focus on very specific issues (BONACCORSI; ROSSI, 2003; NARDUZZO; ROSSI, 2008). Using the cap as an example, a specific group of contributors could focus on optimizing material usage, while another group could focus on generating thread geometries for different standards.

A general impression is that the cases do enable democratization of design solutions, especially for a developing country context. However, the availability and the access cost to digital manufacturing tools was perceived as a possible limitation to the application of such projects. As long as the existence of places for digital manufacturing (Fablabs, Makerspaces, etc.) is limited to few regions, the costs involved in producing an OD artefact (material acquisition, transportation, rates for tools use) make it less attractive. This can be especially true for poorer regions. At the same time, we reinforce the understanding that the need for specialized skills is an impediment to open design (LERNER; TIROLE, 2005; RAASCH; HERSTATT; BALKA, 2009).

It should be taken into account the potential of OD to redefine professional relations and business models. In fact, Open source business models have been discussed by scholars (LAPLUME; ANZALONE; PEARCE, 2016; SAEBI; FOSS, 2015; SHARMA; SUGUMARAN; RAJAGOPALAN, 2002) and existing cases, like OpenDesk, present it as a possible alternative. However, we would like to focus on how changes in professional relations could benefit both professionals and customers. We take the above-mentioned difficulties for design democratization (technology, cost, human capital) as a starting point. In a developing context, we identify an opportunity for professionals to act as intermediates between the demanded knowledge and technology to apply, adapt and improve OD projects for anyone, including those who are not the usual clients of designers, architects or engineers.

In summary, the Open Design ecosystem is still at early stages if we compare it to the development of Open Source software. In this sense, we recognize three main challenges to openness in OD processes. Firstly, platforms for collaborative processes and sharing source files are limited in number and in functionalities. The existence of embedded visualization tools, for instance, could help to track changes in design and facilitate collaboration. Secondly, the preference for proprietary software and file formats restricts collaboration and the application of OD projects. However, we are aware that OS software for computer aided design and parametric design need further development for full functionality. Thirdly, the lack of transparency is a particular issue once it goes against the OD philosophy. Special attention is needed when providing the required documentation and source files for replication of designs.

To conclude, we highlight the limitations of our study. Different conclusions could be drawn if different cases were considered. Nevertheless, our findings are an initial contribution to understand Open Design from the user perspective and the current barriers for design democratization in a developing context.

Conclusion

This study proposed an initial discussion to evaluate OD replicability in the context of a developing country. The adoption of a practice approach allowed us to better understand the limitations, difficulties and, pros and cons of existing cases. However, our findings are preliminary and no generalization should be considered without caution. We understand, for instance, the importance of evaluating OD from different perspectives, e.g. business economic viability, social responsibility and sustainability.

We consider several possibilities for further exploration. First, it is not clear what are the possible pathways to be adopted by professionals, e.g., architects, designers, engineers, in order to adopt the OD approach professionally. Of course, there is a concern regarding economic viability. If designs are freely shared, how do professionals get paid for their work? Existing business models for OD are already a reality. However, few cases exist and little has been written about its application in a developing country context. Second, our cases were limited to the building environment perspective; we understand that a broader understanding of the OD phenomenon would be achieved if cases from other sectors were studied. What are the differences between the different sectors? Is openness addressed equally in different sectors? We understand that this is an actual possibility, especially if we consider the existence of successful OD examples, in terms of collaboration and innovation (RAASCH; HERSTATT; BALKA, 2009). Third, a better understanding of collaborative processes in virtual communities and users' motivations are fundamental to the development of better tools for collaborative design. Studies have shown that there are diverse reasons for users to voluntarily participate in the development of OS software (ROBERTS et al., 2016). Does this also apply to the development of Open Source artefacts?

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5.2 RQ2 – Transposable Limits of Open Design

Introduction

Following the success of the Open Source Movement (OSM) as an alternative for innovation processes and businesses within the software communities, other initiatives and definitions were created in order to broaden the reach of the philosophy behind the OSM. The concept of Open Design (OD) is one example of such derivatives. It refers to the possibility of applying the Open Source model to the development of hardware components tangible products (RAASCH; HERSTATT; BALKA, 2009). Most of the OD benefits are linked to its possibility of providing democratization of the design process (KWON; LEE, 2017; VON HIPPEL, 2005), faster and better innovation processes (SHAH, 2005; VALLANCE; KIANI; NAYFEH, 2001), and citizen empowerment (NASCIMENTO, 2014). In addition, OD is also seen as a promoter of sustainable consumption and production (KOHTALA, 2015). However, little has been explored regarding the use of OD to promote sustainability in developing countries. In order to evaluate whether such benefits of OD are valid we analyze the existing barriers to its widespread adoption.

Although there is no definitive definition to Open Design, there is a consensus that it refers to a gradual condition (BOISSEAU; OMHOVER; BOUCHARD, 2018; OKFN, 2012). Openness can vary (i) at the design process, from non-collaborative to fully collaborative; (ii) at the format of the shared documentation format, from making it available on the web in any format to using only non-proprietary formats; and, (iii) at the license type, from publishing into public domain to maintaining the original author's rights. We articulate openness principles to existing studies in OD. West and O'mahony (2008) distinct transparency from accessibility as two distinct forms of openness. Accessibility is related to easiness of access to source documentation and the possibility given to users to actively contribute to a design project. Transparency refers to the full documentation of a design process to allow users to understand *"what is happening and why"* (West and O'mahony, 2008). Balka (2011 p.82) introduces the importance of "Replicability" as an aspect of openness. The understanding is that a design is not open if the required components to assemble a product are not available. In this sense, OD should guarantee that anyone, professional or amateur, is able to reproduce, optimize and customize such projects. Lastly, design replication is not sufficient if it cannot be modified and adapted for a different context. We argue that a modular approach enables modification. In fact, the concept of modularization is already considered a driver for Mass Customization, Personalization and Co-creation (NIELSEN et al., 2011), problem solving (AFUAH; TUCCI, 2012) and to OD (BONVOISIN, 2016). It contributes to collaborative processes by enabling the user/contributor to focus on very specific aspects of the design (BONACCORSI; ROSSI, 2003; NARDUZZO; ROSSI, 2008), usually on what he is most familiar with.

The four above-mentioned aspects: transparency, accessibility, replicability and modularity are not only complementary to the OD definition but essential principles to its application. In developing countries, there is limited access to technologies, materials and tools. Under such conditions, the potential of OD to promote design democratization is questionable. For example, is it economically viable to produce an OD projects based on 3D Printing and CNC-Milling if the required digital fabrication tools are not locally available or require high financial investments? We are aware that OD is not intended to solve issues on local access to technologies. However, studies present local spaces for community production, such as *Fablabs* and *Makerspaces,* as alternatives to increase decentralized forms of production (HYYSALO et al., 2014; NASCIMENTO, 2014).

Methods and Tools

In this study, we address the gap related to the adoption of OD in developing countries by considering both openness principles and sustainability indicators. Next, we introduce the methodological approach used to (1) define sustainable indicators and openness principles, (2) select the OD cases and (3) analyze the respective cases. A list of recommendations for enabling OD practice in a developing country context is presented and discussed. We adopt the Sustainable Development Goals (SDGs) (UNITED NATIONS, 2015) to address the three dimensions of sustainable development with a more proactive approach (LEVÄNEN et al., 2016). Each of the 17 Goals have targets oriented to specific actions such as to (1) ensure access to water, energy and food, (2) reduce inequalities, (3) promote sustainable consumption and (4) promote decent work and innovation.

We focus on the strengths and weaknesses of OD to promote social inclusiveness (SI) while guaranteeing economic viability (EV) and environmental responsibility (ER). For this purpose, we adopt nine indicators distributed in two sets. The first set measures openness aspects based on four Open Design principles discussed in the literature. The principles consist on accessibility, transparency, modularity and replicability. The second set incorporates part of the Sustainable Development Goals (SDGs) to measure the above-mentioned aspects of SI, EV and ER. Five indicators are used in this case. The indicators are related to two temporal constraints. First, we introduce a critical view on the present limitations for OD and, second, we develop possible pathways for addressing such limitations. It is important to note that the indicators are not specific to each of the sustainability aspects but present overlapping relations. The stimulation of local companies for instance, has environmental impacts (decreasing the need for transportation) and provides better opportunities (social and economic). We adopt a similar approach to studies on frugal innovations (LEVÄNEN et al., 2016), and Do-it-Yourself production (BONVOISIN; PRENDEVILLE, 2017).

Table 10 - The nine indicators to measure sustainability and opennessintroduces the sustainability indicators, the openness principles and the reasoning we adopted to analyze the selected cases.

Table 10 - The nine indicators to measure sustainability and openness

Sustainability Indicators	Reasoning
Does it require specialized skills for implementation?	The need for specialized skills decreases social inclusiveness. SDGs 4,5 and 8.
Does it stimulate the creation of local jobs and companies?	It stimulates better job opportunities and higher income. SDGs 1, 5, 8 and 10.
Does it improve access to basic services, (water, energy and food)?	It helps to overcome the lack of infrastructure for basic sanitation. SDGs 2, 6, 7 and 9.
Does it stimulate sustainable consumption of natural resources?	It minimizes the exploitation of natural resources. SDGs 9, 12, 14 and 15.
Does it increase energy efficiency?	It reduces the consumption of non-renewable resources and GHG emissions. SDGs 7, 9, 12 and 15.
Openness Principles	
Modularity	It contributes to collaborative processes enabling the user/contributor to focus on very specific aspects of the design.
Replicability	It relates to the possibility of reproducing a physical artefact using similar settings as of the original design.
Accessibility	It relates to the easiness of access to the source file, especially, in non-proprietary formats. It denotes the possibility of users to actively contribute to the development of an OD project.
Transparency	It relates to the full documentation of a design process in order to allow contributors/users to understand "what is happening and why" (West and O'mahony 2008).

Selection of Cases

The selection of the cases consisted on a four-round process. Although OD examples exist in many industries, such as clothing, biotechnology and pharmaceuticals industries (Lakhani & Panetta, 2007), we limited the cases to the field of architecture and urban design. First, we searched existing literature on OD cases in Scopus, Google Scholars and Web of Science databases. Second, we decided to search the web for projects, repositories or companies focused on OD. This search resulted in a higher number of results and 21 potential cases were identified. The third stage, involved a pre-analysis of each case and a grouping process. We developed four major groups considering the scale and nature of each case and the information available. Finally, we selected two cases of each group and proceeded to the evaluation stage. It is important to highlight that besides the 21 cases we identified (Table 11); other examples were found in repositories for sharing design projects. We excluded such examples from our analysis because we aimed at reliable and well-structured cases.

Next, we introduce the grouping process and the evaluation tools we adopted. The component scale refers to any element that cooperates or works together with other elements to form a system. In this sense, a window, a door or a roof constitute a system and a wood frame, a lock and a tile are some of the components of these systems. The system/organizational scale consists on the scale where general and broader functions of a building are performed. At this scale, the user is indirectly connected to the function, although benefiting from it. The enclosure of a building, for example, separates the exterior from the interior of a building. Table 12 summarizes the selected cases, their domains and general information.

Table 11 - List of the 21 OD cases identified. The selected cases are identified (bolded).

Case	Source	Sector
OpenDesk	https://www.opendesk.cc	Furniture Design
Mozilla Factory Space	http://os-furnitures.tumblr.com	Furniture Design
MonoDesign	https://monodesign.com.br	Furniture Design
Dosuno Design	http://www.dosunodesign.com	Furniture Design
Open structures	http://openstructures.net	Furniture Design
Home-Assistant	https://www.home-assistant.io	Home Automation
Calaos	https://www.calaos.fr/fr/	Home Automation
Domoticz	http://www.domoticz.com	Home Automation
Open Hardware	https://www.openhardware.io	Home Automation
Openmotics	https://up.openmotics.com	Home Appliance / Automation
Open Energy Monitor	https://openenergymonitor.org	Home Appliance
Faircap	http://faircap.org	Water Consumption
Caminos de Agua	http://www.catis-mexico.org	Water Consumption
One Community	https://www.onecommunityglobal.org	Energy-Food-Water Nexus
Sunzilla	https://sunzilla.de	Energy generation
Aker	https://akerkits.com	Food Growing
Open Agriculture Initiative	https://www.media.mit.edu/groups/open-agriculture-openag/overview/	Food Growing
Elemental	http://www.elementalchile.cl	Housing projects
Paperhouses	http://paperhouses.co	Housing Projects
Wikihouse	https://wikihouse.cc	Housing Projects
Bricksource	Parametric brickwork patterns	Facade Design

Table 12 - Summary of the domains each case relates to

Cases	Domain			Description
	Digital	Physical Component	Physical System	
OpenDesk			X	Furniture Designs
Mozilla Factory Space		X	X	Furniture Design
Domoticz	X	X		Home Automation
home-assistant	X	X		Home Automation
Aker			X	Food Growing
OpenAg	X	X	X	Food Growing
Sunzilla	X	X	X	Solar Energy panels
Caminos de Agua	X	X	X	Water solutions

To evaluate the cases, we first linked all the six indicators to related Sustainable Development Goals (SDGs). Each indicator was associated to the temporal dimensions (present and future), and the four principles of openness, namely Transparency (TR), Accessibility (AC), Replicability (RE) and Modularity (MO). Then, we familiarized with all the available data of the selected cases. For the present context and for each case, three values were considered, -1 for negative, 0 for neutral and +1 for positive performance. For an optimum future scenario, the same principles were considered. After that, a set of pathways to optimize the use of OD in a developing country context was developed. The selected cases are introduced next.

OpenDesk

OpenDesk is a London based company which distributes furniture designs under Creative Commons license, mainly under non-commercial restrictions. The designs are distributed to end-users as a DIY digital fabrication file or to local manufacturers, which produce them commercially. When local manufacturers produce the furniture, the amount paid by the consumer is distributed between the maker, the designer and OpenDesk. The documentation uses .DXF files for generating CNC-milling paths and .PDF files with general instructions.

Mozilla Factory Space

Designed by Nosigner, Mozilla Factory Space is a office based in Tokyo which is part of the Mozilla Foundation. The Foundation is known for the development of Open-Source softwares and solutions for the web. The office design adopted the concept of Open Design and all the furniture project details are made publicly available in .DXF, .PDF and .EPS files. The documentation is given in form of assembly instructions and drawing details for CNC-milling.

Domoticz

Domoticz develops open source home automation platform which operates in various Operating Systems, proprietary or not. The documentation is provided in form of instructions for installation, setup, customization and operation. Stable and Beta installation packages are provided and the source code is available at Github. The initiative does not develop any hardware component; however, it provides a list of compatible components, e.g., weather and temperature sensors.

Home-assistant

Similar to Domoticz, Home-assistant is a platform for home automation based on Raspberry Pi. The documentation is also given in form of instructions for installation, setup and operation. It supports integration of over 1000 hardware and software components including sensors, switches, cameras, alarms and presence sensors. An instruction for integrating the component to the platform is given for each component.

The development community feeds a repository of examples on how to use the home-assistant and forum provides support for users.

Aker

Aker develops garden kits for urban farming under a Creative Commons Sharealike 4.0 license. There are no commercial restrictions applied, however any modification or optimization to the original design should be distributed under the same license. Documentation is distributed in .DXF files for CNC-milling and assembly instructions are also provided. The company website provides a community forum for users. Lastly, it is also possible to buy the kits directly from the company.

Open Agriculture Initiative (OpenAg)

OpenAg is an initiative hosted at the MIT Media Lab. Its mission is to "create healthier, more engaging, and more inventive future food systems." (Open Agriculture Initiative, 2016a). Currently, there are several projects under development. For the purposes of this study we will focus on the Personal Food Computer project. It is a small sized and controlled environment platform for growing food. Documentation is available in .DXF, .SLDPRT, .PDF file formats for CNC-Milling and 3D-Printing. A Bill of Materials is provided for electronic components. Instructions and a Community Forum is also available for discussion.

Sunzilla

Sunzilla is an Open Source solar-powered generator for off-grid supply licensed under a Creative Commons Attribution-Sharealike 2.5 license. Documentation is not available at the Company's webpage. However, it is possible to access it at Instructables or Wikifab repositories. It consists on .PDF and .DXF files for laser-cutting or CNC-

Milling. We were not able to identify the existence of a forum for development collaboration or discussion.

Caminos de Agua

Caminos de Agua is a nonprofit organization located in Mexico which develops solutions for safe water supply and consumption. The organization has over 100 projects implemented in Mexico mostly based on Rainwater Harvesting Systems and Ceramic Filters. No CAD documentation is available at the Organization's Webpage, however .PDF files are available with instructions for building Ceramic Filters, Rainwater Harvesting Systems and Biochar filters.

Findings and Discussion

Table 13 presents a summary of our findings. It consists on the evaluation of each case considering the nine indicators previously mentioned. The evaluation process considered the application of the OD cases in a developing country context. More specifically, we addressed it based on our knowledge, experience of the Brazilian availability of materials, tools, machines and skilled professionals. We also explored the existing discussion forums to identify if projects were already developed in Brazil. For example, Home Automation components to assembly Domoticz and Home-assistant projects are easier to find if compared to OpenAg components. At OpenAg forum, for instance, one of the users highlights the need to adapt parts to the project because of some component's unavailability. As for Table 14, it summarizes the current characteristics found in the OD cases. We highlight current limitations and present positive aspects. The second column introduces recommendations for developing a pathway for addressing such limitations and guaranteeing full democratization of OD.

Table 13 - Summary of the findings

	Open Desk	Mozilla	Do-motiz	home-assist.	Aker	OpenAg	Sunzilla	Caminos
Does it require specialized skills for implementation?	-1	1	-1	-1	-1	-1	-1	1
Does it stimulate the creation of local jobs and companies?	1	0	1	1	1	0	1	1
Does it improve access to basic services (water, energy and food)?	0	0	1	1	1	1	1	1
Does it stimulate sustainable consumption of natural resources?	0	1	0	0	0	0	1	1
Does it increase energy efficiency?	1	1	1	1	1	-1	1	1
Principles								
Is it Modular?	0	1	1	1	1	0	0	0
Is it Replicable?	1	1	1	1	1	-1	1	-1
Is it Accessible?	-1	0	1	1	0	1	-1	-1
Is it Transparent?	0	0	1	1	0	1	-1	0
TOTAL	**1**	**5**	**6**	**6**	**4**	**0**	**2**	**3**

Table 14 - Current aspects on OD and Future recommendations.

Current Aspects of Open Design	Future recommendations
• Cases demand specialized skills, especially in computer programming, electronics and CAD design. Language is a barrier. • The OD cases enable favorable environment for creating local jobs. • Cases are either dependent on high technology or frugal innovations. However, it is important to highlight the potential of home automation for improving access to basic services. • Energy efficiency increases because of decentralized production processes which reduces the need for transportation. However, the energy source requires particular attention. • Modularity was perceived in cases which are scalable and adopt recycling and reusing practices. Modularity in digital domain cases is higher than physical cases. • Replicability is considerable high among the cases analyzed. Restrictions are limited due to the lack of information or components not easily available in developing countries. • Proprietary file formats restrict the access to source files. A more problematic aspect is the use of restricting licenses and the nonexistence of open processes for collaboration in cases which commercially explore the final product. • Transparency is restricted when missing information for production and assembling is provided. Some of the cases do not have the full documentation available at the project's host page.	• To share full documentation of projects targeted for beginners. • To increase the number of facilities for digital fabrication, such as *Fablabs* and *Makerspaces*. • To implement training programs for operating digital manufacturing tools and machines. • To develop alternative designs for recycled, reused and/or local material resources. • To develop of Open Source Software and file formats, and optimize collaboration platforms for physical objects. • To stimulate the use of different languages in documentation files and instructions. • To develop standardized components repository for use in all types of physical projects. • To stimulate the adoption of OD in creative industries and services, e.g., architecture and urban design. • To develop policies which stimulate the adoption of OD projects in public sectors. • To develop repositories for measuring the environmental impact of OD projects. • To create repositories with local materials specification for design compatibility.

Social Inclusiveness

A number of studies present successful cases of how OD improved design democratization (KWON; LEE, 2017; VON HIPPEL, 2005). However, our findings show that OD is dependent on the existence of skilled professionals, tools and machinery. In a developing country context, this dependency might restrict the adoption of an OD project if such structure is not available at the local level. The lack of such *infrastructure* increases the costs involved in producing an OD artefact (material acquisition, transportation, rates for tools use). This is particular true for rural communities and small cities. As expected, solutions based on material recycling and reutilization (Mozilla Factory Space and Caminos de Agua) are easier to be replicated in different contexts. However, incomplete or inaccurate documentation, such as we observed in Caminos de Agua solutions, limits the correct implementation of such OD solutions.

At large, OD projects are linked to digital fabrication processes which we already pointed as a limiting factor for social inclusiveness. At the same time, we add here a less debated aspect in OD communities: the language barrier. It was not surprising that English is the most common language used in collaboration processes and design documentation. Should OD projects stimulate the generation of ramifications in other languages? We believe so, especially if we consider that in developing countries English is not spoken by the Majority of the Population. In Brazil, for instance, English speakers represent 5 percent and of the total population (BRITISH COUNCIL, 2014).

Lastly, we envision better possibilities because of the expansion of local *Fablabs* and *Makerspaces* supported by Educational Institutions (BLIKSTEIN; KRANNICH, 2013), and the development of OD manufacturing tools, such as RepRap, a self-replicating 3D printer. We also suggest the adoption of OD processes by professionals in the construction sector. We understand it as an alternative to proximate them to those who are not seeing as usual clients. Self-construction is a widespread practice in countries like Brazil (MONTEIRO et al., 2006). In this sense, OD could guarantee better designed solutions for new or incremental projects.

Economic viability

Economic viability relates both to the commercial viability and to the financial benefits of adopting OD. From the commercial viability perspective, OD stimulates new businesses models (LAPLUME; ANZALONE; PEARCE, 2016; SAEBI; FOSS, 2015) focused on services instead of manufacturing. OpenDesk, for instance, distributes furniture design projects for personal use at no cost. However, they offer services for projects customization and linking final consumers to local makers, i.e., specialized places for digital fabrication. Other possibilities are envisioned if we consider, for example, home-automation services based on Open Source projects like Domoticz and Home-Assistant. We also understand that the adoption of OD by the public sector would contribute to the expansion of small-scale manufacturers and to the economic sustainability of such projects.

From the user perspective, the financial benefits are also linked to the availably of infrastructure for manufacturing OD artefacts. At the same time, most of the cases we observed do benefit users in financial terms. Sunzilla and Caminos de Agua minimize costs for access to energy and water while OpenAg and Aker enables food production. Finally, automation projects can increase energy efficiency controlling, for instance, room temperatures and light intensity.

Environmental Responsibility

We noted that OD cases have beneficial potential to energy and natural resources consumption. Decentralized production minimizes the need for transportation which decreases energy consumption and greenhouse gas emissions. Again, this condition is strengthened if local materials are available. Energy is also benefited from digital domain solutions, such as Domoticz, Home-Assistant and Sunzilla. The first two enable the user to measure energy consumption and automate lighting operations, for instance. Sunzilla provides solar energy panels at relatively low-cost production.

OpenDesk, Aker stimulate the use of sustainable materials by producing artefacts using certified wood panels. This is possible if the production is controlled by the companies. There are no restrictions applied to the use of non-certified wood by final users. At the same time, there are no artefacts designed to minimize material consumption in both cases. The possibility of disassembly and subsequent use in other projects is also not supported. The Mozilla Factory Space (MFS) and Caminos da Agua, on the other hand, stimulate recycling and reutilization practices. MFS projects use everyday materials like plastic boxes and pallets to function as plant pots or elevated floor tiles. Although it uses plastic objects, we understand it as beneficial once it enables recycling and reutilization processes.

Despite such benefits, we identify the need for quantitative approaches to measure energy efficiency and material consumption impact. In this sense, the development of open data repositories to measure carbon footprint, for example, could help designers to choose the best materials for specific locations in terms of environmental impact.

Modularity, replicability, transparency and accessibility

Although there is no definitive definition for Open Design, we understand openness as a gradual concept. It considers aspects of documentation format, design processes and license attribution. Generally speaking, OD projects based on the digital domain are usually more Open than those based on the physical domain.

Table 13 shows that such projects tend to address all principles of openness better than physical designs. This is not an unexpected result. The sharing of information and collaborative processes are easier to be performed in virtual environments, require less financial support and have well-structured platforms for collaboration. Existing platforms still do not meet the needs for collaboration in artefact design.

Modularity is already addressed in OpenSourcre software development. In Domoticz and Home-assistant examples, modularity significantly improves the compatibility to other existing components. Besides that, it allows contributors to focus on very specific issues (BONACCORSI; ROSSI, 2003; NARDUZZO; ROSSI, 2008) but also facilitate the adjustment of design specifications to local standards (language and components), enable design scalability (Aker) and cradle-to-cradle processes. Although some cases presented certain degree of modularity, if we consider joints specification (OpenDesk) and the use of smaller components (Sunzilla), we classified them as neutral because there was no available information related to modularity.

Replicability was well addressed by most of cases. The reasons are that the needed documentation for producing, assembling and operating the design artefacts, and installing the digital cases, were easily available for download. Limitations apply to Sunzilla and Caminos de Agua. Sunzilla did not enable ways to obtain the design documentation at their project's page. Source files and instructions were found in a repository for DIY projects. The case of Caminos de Agua is less critical once it shares construction instructions for producing their projects, but some of the instructions are incomplete.

Accessibility of OD is limited due to the use of proprietary file formats and software. Some Opensource software's are capable of importing different file formats however, such process is never completely reliable and might demand further adjustments to the imported documentation. Another aspect to consider is licensing restrictions for commercial purposes. The restrictions are conflicting to openness principles which guarantee source documentation publicity for anyone and for any purpose (OKFN, 2012). Lastly, some projects are not open for collaboration processes which minimizes the potential for innovative approaches, modularity and adaptations to the original design.

Transparency is well observed in projects which stimulate the existence of community forums for design development, discussions and inquiries about functionalities. In this sense, Domoticz, Home-Assistant and OpenAg are particular transparent. Cases which are commercially explored presented lower degree of transparency. We consider it as a possible coincidence which should be further investigated. However, the lack of transparency deserves attention once it goes against the OD philosophy.

Limitations of the study

We highlight the limitations of our study based on the number of cases we investigated. Furthermore, deeper investigation of the selected cases would be necessary to confirm or contradict these preliminary findings. We draw two observations related to our study. First, our qualitative indicators for social inclusiveness, economic viability and environmental responsibility was built based on the SDGs. We suggest the use of quantitative measurements tools as an alternative to obtain more consistent results although they restrict general observations. Second, the openness principles are already adopted in literature. Transparency and Accessibility principles are present in OD definition if we consider, collaborative processes and access to full documentation design. Replicability and Modularity, on the other hand, are less obvious and might be subject to the researchers' points-of-view. These issues can be addressed by immersive and practice-based researchers or through the development of quantitative measurements.

Conclusion

In this study we present OD cases related to Architecture and Urban Design. We adopted a non-restrictive approach to both sectors to include most of the cases we initially found. This study is a first attempt to understand the current limitations to a widespread adoption of OD in developing countries by the construction sector, including architects, urban designers, other professionals and amateurs. We also present a set of initiatives transpose such limitations in future contexts.

We consider several possibilities for further exploration. OD enables new forms of businesses and changes in traditional professional practices. The actual economic benefits for professionals and consumers is a subject to be explored in future studies. Social inclusiveness and environmental responsibility depend on higher democratization processes and data availability. Consequently, the development of tools and collaboration platforms are needed to improve the quality of the OD ecosystem.

References – RQ 2

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5.3 RQ3 - Challenges in replicability of Open Design - a case study of Residential Rainwater Harvesting

Abstract

Open Design (OD) holds potential to serve as an approach to respond to many kinds of global challenges, but from the perspective of replicability, it faces significant challenges. We adopted the Residential Rainwater Harvesting Systems (RWHs) as a case study to investigate issues related to replicability of OD. We identified the main components of the RWHs and analyzed the replicability potential of each component through a set of OD principles. The analysis revealed different limitations related to materials and manufacturing tools that local communities may face when they are trying to make use of OD in water management. The results suggest that in order to explore the full replication potential of OD projects, four general topics need to be considered: (1) the adoption of a "design-for-frugality" mindset in design processes, (2) the possible lack of access to digital manufacturing technologies and specialized knowledge, (3) concerns regarding liability and safety of OD projects and (4) the importance of parametric design to simplify complex objects.

Introduction

The concept of Open Design (OD) has increasingly gathered attention amongst scholars, grassroots communities and companies during the last ten years. Aitamurto et al. (2015) define OD as "provid[ing] public access to participation in the design process and to the product resulting from that process, as well as the data created in the design process, including technical details and other data and content gathered or generated during the process." Commentators of OD have underlined the multifactorial nature of the concept of openness (e.g. BALKA; RAASCH; HERSTATT, 2014; BONVOISIN; MIES, 2018), being a combination of accessibility - the degree of access to the design development process -, transparency - the availability and quality of the design process and outcomes -, and replicability - the possibility of self-assembly of a product in a Do-it-Yourself (DIY) approach. Hence, accessibility, transparency and replicability are the three principles adopted in the literature to frame the concept of OD.

OD promotes distributed, participatory and decentralized design and production processes, which are necessary in efforts to respond to wide-scale sustainability challenges (KOSTAKIS et al., 2015). Also, it has been suggested that OD promotes the development of sustainable products and consumption practices (BAKIRLIOĞLU; KOHTALA, 2019; BONVOISIN, 2016), helps individuals and communities to overcome specific global problems at the local level - e.g. creating OD devices for helping beekeepers to improve honey yield (PHILLIPS et al., 2014) - and promotes the development of technological solutions to sustainability challenges, such as energy production (KADISH; DULIC, 2015). Through reproduction, OD can increase access to technologies, which are important in local adoption to changes in environmental conditions. This is how OD can contribute to sustainable development.

However, recent research findings point out that design replicability is a significant challenge to scale-up OD (KOSTAKIS et al., 2015; OSTUZZI et al., 2016). Salient hurdles are the need for access to a spectrum of technologies (e.g. personal computers and digital manufacturing tools), multi-language documentation of design processes and outcomes (KOSTAKIS et al., 2015), and design processes that have a "design for appropriation" approach (OSTUZZI et al., 2016), referring to adaptation/modification of technologies or designed objects to serve local specific needs, i.e. adapting the design to the context of its use.

In this study, we explore by means of an exploratory study the challenges that replicability of OD faces. For this purpose, we identified a global challenge with local implications that could benefit from the innovative approach of OD: water safety. We adopted the Rainwater Harvesting Systems (RWHs) for a specific context - locals in vulnerable conditions - as our research object. The rationale for adopting the RWHs is both related to the technology complexity and its potential to improve human living. First, RWHs can be individually installed, which strengthens DIY approaches and self-organization. Second, utilization of RWHs is directly linked to one of the Sustainable Development Goals (SDGs) - a set of 169 targets to address global challenges. For instance, the SDG 6 - Clean Water and Sanitation - refers to the universal provision of safe and affordable drinking water as one of its targets. Finally, RWHs enable the implementation of decentralized infrastructures for water supply, having indirect relation to other SDGs, e.g. Industry, Innovation and Infrastructure, and Sustainable Cities and Communities.

We conducted a systematic literature review to identify specific design aspects and components of RWHs important for its correct functioning. Following that, we assessed the replicability potential of the RWHs components based on OD principles. Then, we highlight four major limitations for replication in OD and indicate possible pathways to overcome it. The main outcomes of the article highlights existing challenges for replicating OD projects in different contexts and indicate viable ways for addressing such challenges. From a practical perspective, the results can help practitioners to improve OD processes and designs in order to facilitate replication in different contexts and orient projects that consider the adoption of OD about existing challenges to its widespread adoption. It can also contribute to the evaluation of OD processes, especially from the replicability perspective. Finally, the limiting factors for replicability can also instigate researchers to explore such limitations in-depth using different cases.

Open Design and Do-it-Yourself

OD is characterized by two forms of openness: product openness, meaning the availability of product-related information for reuse and process openness, meaning the possibility for any interested person to take part in the collaborative development process (AITAMURTO; HOLLAND; HUSSAIN, 2015; BOISSEAU; OMHOVER; BOUCHARD, 2018). Furthermore, researchers attribute to OD the principles of (1) accessibility, (2) transparency and replicability (3). Accessibility refers to the easiness of a participant to contribute to a product development process in different ways - suggestions, discussions or active modifications. Transparency comprehends the quality of information resulted from the design process in order to allow any user to understand "what is happening and why" (WEST; O'MAHONY, 2008). Finally, replicability consists of the possibility of self-assembly of the product. It is dependent on the availability of individual components and thus the possibility for the hand assembly of the product and the existence of transparent and accessible information for the production of OD objects (BALKA, 2011). It is not only important for the final design production but also as part of collaborative processes as it enables users to test and improve initial versions of the design.

Recent researches indicate openness - the attribute of an OD project - to be gradual (BOISSEAU; OMHOVER; BOUCHARD, 2018; BONVOISIN; MIES, 2018). According to that understanding, OD project can be more or less open depending on factors such as (1) the process of design, from non-collaborative to fully collaborative; (2) the format of the shared documentation format, from making it available on the web in any format to using only non-proprietary formats; and, (3) the license type, from publishing into public domain to maintaining the original author's rights. The principles of accessibility, transparency and replicability directly affect openness and can, therefore, be adopted to evaluate openness of different design processes. Bonvoisin and Mies (2018), for example, propose a "rating scheme" called "Open-o-meter". The tool, as proposed by the authors, is an initial move towards the definition of openness standards.

It defines a set of eight criteria, based on both the product and the design process, to evaluate how open is a project. Although it takes into account replicability based on transparency and accessibility factors, such as providing a bill of materials for specific designs, the scheme does not measure replicability from the DIY perspective.

In parallel to OD, recent evolutions in the Do-it-Yourself (DIY) phenomena are linked to the advent of digital design tools, digitally-driven production technologies and the Internet (access and speed) (FOX, 2014). Such context is claimed to be responsible for the renaissance of craftsmanship (ROGNOLI et al., 2015) and the emergence of a maker movement (HYYSALO et al., 2014). The increase of online platforms for design sharing, e.g. Instructables and Thingiverse, and small-scale workshops for digital fabrication, e.g. Fablabs and Makerspaces, also contribute to the argument that this new form of DIY enables the production of more complex products not often available locally. However, we highlight that it is dependent on access to a set of digital technologies - for design and manufacture - and technical knowledge - to design and interpret design plans - (KOSTAKIS et al., 2015). Designing for different depths of DIY, thus minimizing the need for specific tools (BONVOISIN; GALLA; PRENDEVILLE, 2017), and the development of intuitively understandable CAD tools with user-friendly interfaces (SONG; GUIMBRETIÈRE; LIPSON, 2009) are examples of viable alternatives to minimize the dependency on technology and specific knowledge, e.g. digital modeling.

Materials and Methods

Rainwater harvesting systems review

We conducted a Systematic literature review on RWHs to identify (1) the system design requirements, (2) the main obstacles that prevent a broader adoption of the systems and (3) the common issues associated with the system functioning. First, we used the search expression “Rainwater Harvesting (AND) Case” on Scopus and Google Scholar limiting it to the period of 1998 - 2019. The expression was applied to the fields: “title”, “abstract” and “keywords” and it returned a list of 351 results (excluding books, book chapters and reviews). The results included 288 articles and 63 conference papers. In the second round the title, abstract and keywords were considered to identify whether the case studies were related to small scale projects (e.g. single-family dwellings) and whether the obstacles and common issues of RWHs were mentioned. The remaining 103 articles were read in their totality in order to identify those which mentioned existing design features/components associated to specific issues (e.g. water quality) or proposed design solutions. Finally, 20 studies were selected. Backwards citation tracing identified 13 additional references complying with the requirements of our study, extending the number of considered articles to 33.

Articles analysis

The 33 articles were used to identify the design features (DF), specific functions and common issues associated with RWHs. In order to structure our analysis, we limited it to the hardware domain (HD) of the system, i.e. the physical aspects that (i) correspond to its practical functionalities, (e.g. filtering and collecting); and (ii) affects the system performance because of poor design. For instance, material deposition on the rooftops - which leads to water contamination - is included in our analysis once hardware adjustments minimize its negative impacts. Hence, our analysis does not take into account the second domain, which we defined as the System Standards Domain (SSD). It refers to the briefing phase when a set of technical requirements for the correct functioning of the system, considering its input variables (e.g. dimensions and variables) and procedure standards (e.g. production, installation and maintenance) are defined. The water tank, for example, is part of the HD but its design depends on parameters such as the roof size, runoff volume, and demand which are part of the SSD. Our focus on the HD enables us to discuss it from the manufacturing perspective considering aspects such as materials, tools and standardization.

The articles analysis consisted of associating specific aspects to a set of systems and components used in RWHs. Each component was related to a specific system: the collector system, the storage system and the supply system. In Table 15 (Appendix A), we present a summary of the main aspects discussed in the literature relating them to their specific systems and illustrate it by highlighting some excerpts from specific studies.

We also collected 10 manuals produced by NGOs, NPOs, public agencies and international organizations. The manuals introduce techniques to produce RWH components (HARTUNG; HEIJEN, 2016), assemble and install the complete system; present design recommendations and good practices (KALIMUTHU, 2016; RAINWATER HARVESTING RESEARCH GROUP - RHRG, 2001), show the risks associated with low maintenance and how to execute it (THOMAS; MARTINSON, 2007) and present the benefits of adopting it. The manuals were used to identify the design features of the RWHs and also the design maturity of each feature. For example, the variety of water tanks for storage available indicate a wide range of possibilities in terms of complexity, materials and configuration. Some also present the design plans and construction methods for different tanks, indicating a certain degree of openness.

Table 15 - Aspects of RWHs for water quality (Appendix A)

Aspects	System	References	Excerpt example
Taste / Odour	Collector, Storage, Supply	Amin and Han, 2011; Baguma et al., 2010; Campisano et al., 2017; Daoud et al., 2011; Kim et al., 2005; Kim et al, 2016; Mayo & Mashauri, 1991; Mwenge Kahinda et al., 2007; Nalwanga et al., 2016; Nguyen et al., 2013; Schets et al., 2010; Thomas, 1998	*"Materials used for construction such as cement and lime may impair the taste of water and scare away consumer."* (Mayo and Mashauri, 1991)
Component Materials	Collector, Storage, Supply	Arku, F. et al., 2015; Baguma and Loiskandl, 2010; Burt and Keiru, 2009; Campisano et al., 2017; Chang et al., 2004; Daoud et al., 2011; Ghimire and Johnston, 2015; Helmreich and Horn, 2009; Kim et al., 2005; Lo and Gould, 2015; Lye, 2009, 2003; Mayo and Mashauri, 1991; Morales-Pinzón et al., 2015b; Mwenge Kahinda et al., 2007; Nalwanga et al., 2016; Nguyen et al., 2013; Opare, 2012; Schets et al., 2010; Simmons et al., 2001; J. Song et al., 2009; Thomas, 1998; Tobin et al., 2013	*"(...) when subsidies in the form of RWH construction materials are provided, the chances of having a RWH system installed seem more."* (Baguma and Loiskandl, 2010)
Material Deposition	Collector, Supply	Arku et al., 2015; Baguma et al., 2010; Burt and Keiru, 2009; Campisano et al., 2017; Chang et al., 2004; Daoud et al., 2011; Han and Ki, 2010; Helmreich and Horn, 2009; Kim et al., 2005; Kus et al., 2010; Lee et al., 2016; Lye, 2009; Magyar et al., 2007; Mayo and Mashauri, 1991; Morales-Pinzón et al., 2015b; Mwenge Kahinda et al., 2007; Nalwanga et al., 2016; Nguyen et al., 2013; Opare, 2012; Schets et al., 2010; Simmons et al., 2001; Thomas, 1998; Tobin et al., 2013	*"(...)This suggests that after the contact with the roof, the rainwater was significantly contaminated by biopolymers and humic substances. This could be a result of atmospheric deposition."* (Kus et al., 2010)
Maintenance	Collector, Storage	Baguma et al., 2010; Campisano et al., 2017; Daoud et al., 2011; Gomes and Heller, 2016; Lo and Gould, 2015; Lye, 2009; Mayo and Mashauri, 1991; Mwenge Kahinda et al., 2007; Schets et al., 2010; Simmons et al., 2001; Thomas, 1998; Tobin et al., 2013	*"However, for other domestic purposes, (...) proper preventive and maintenance procedures may guard the microbiological quality and safe use of stored rainwater."* (Schets et al., 2010)
Positioning	Storage, Supply	Campisano et al., 2017; Han and Ki, 2010; Magyar et al., 2007; Mayo and Mashauri, 1991; Mwenge Kahinda et al., 2007; Nguyen et al., 2013	*"(...)And water outlets located at the bottom of the tank let sediments flow out with supplied water"* (Han and Ki, 2010)

Open Design for self-production

At this stage, we defined the OD principles of transparency (TR), accessibility (AC) and replicability (RE) based on existing definitions and common practices within online communities. However, in this study we considered that both TR and AC are principles that enable RE. In other words, RE is a core principle from which TR and AC are dependent. This is a particular condition we adopted to proceed with our analysis and it means that other factors related to TR and AC might be excluded because they are not related to RE.

We also defined the design principles that enable RE in a DIY approach based on the understanding that peer production is dependent on access to capital and resources

(KOSTAKIS et al., 2015) and the less dependent on both the more replicable a design is. We based our principles on the study conducted by Bonvoisin et al., (2017). The authors outlined 14 design principles towards DIY processes based on existing OSH products. We adopted those which fit the purposes of our study, limiting it to factors such as (a) material availability, (b) material variety, (c) tools needed, (d) personalization and (e) depths of manufacturing complexity.

In summary, there are two procedures considered. First, we analyzed design processes and documentation and, second, the design principles applicable to RWHs. Therefore, an analytical framework is proposed based on the following replicability definition: Replicability refers to the possibility of reproducing a physical artefact, i.e. self-producing a product. It is dependent on (a) accessible design processes, (b) transparent design documentation and (c) the availability of capital resources, material and manufacturing technologies. Finally, eight questions and parameters are proposed to evaluate the replicability potential of each RWHS component (Table 16). We adopted a product profile chart named "Harris Profile" to evaluate how each component relates to each parameter. The adopted profile chart model was initially proposed by Harris (1982) and it indicates the strengths and weaknesses of design alternatives. It consists of a four-columns chart, weighted from -2 to +2. Since it is used also for visual interpretation, when a -2 or +2 grade is given, the -1 or +1 cells are also marked.

Table 16 – Replicability parameters for OD and DIY (Appendix B – Part A and B)

		Replicability in OD	Statement	Classification Guidelines
Accessibility	1.a	What is the quantity and/or quality of information needed to replicate the hardware components?	Higher quantity/quality of information makes openness more difficult.	+2 Instructions and manuals +1 2D CAD drawings and plans -1 3D Models (low complexity/single components) -2 3D Models (high complexity/multiple components)
Transparency	1.b	How complex are the components in order to allow any user to participate in product development, including making suggestions and improvements?	Technical complexity demands expert knowledge to develop/modify designs. Suggestions are less dependent on knowledge but still affected by technical complexity	+2 Low complexity (No user experience) +1 Low complexity (User experience, e.g. design tools) -1 High Complexity (Technical Experience for structural modifications, e.g. storage dimensioning) -2 High Complexity (Technical Experience for specific modifications, e.g. filtering methods)
	1.c	What are the requirements for user participation in production development, including suggestions and improvements?	Higher requirements make the process less open. Ex. Computaional models are less open than Wiki/instructions development	+2 Textual suggestions are sufficient to improve designs +1 Textual and drawings are sufficient to improve designs -1 Knowledge in 2D CAD and 3D modelling tools -2 Knowledge in 2D/3D modelling and materials performance
		Replicability in DIY	**Statement**	**Classification Guidelines**
Materials	2.a	Are the components' materials widely available?	Availability of materials makes designs more likely to be replicated	+2 Non-processed materials without decreasing performance +1 Materials do not need special tools, e.g. Cement -1 Materials need specific tools, e.g. Aluminium sheets -2 Very specific materials, e.g. Biofilters
	2.b	Can the component be produced with a high variety of materials?	Material flexibility increases the chances of DIY approaches	+2 High variety of materials (+5 types) +1 Medium variety of materials (+3) -1 Low variety of materials (+2) -2 Low variety of materials (1)
	2.c	Can it be produced with standard tools?	Accessible and standard tools facilitate production processes	+2 Standard tools (mainly manual) +1 Standard tools (electric powered) -1 Non-standard tools (metal folding) -2 Very specific tools (3D-Printing, CNC-Milling)
Design Features	3.a	Does it enable flexible design? Can it be tailored according to the context?	Flexibility in design helps the design production in different contexts	+2 Standartization does not affect the system performance. Design appropriation in different locations need minor modifications +1 Standartization might decrease system performance. Complex modifications are needed to adapt designs -1 Standard components might not work in specific locations and adaptation requires structural modifications -2 Components' design cannot be adjusted
	3.b	Can it be designed for different depths of DIY?	Different locations have access to different tools/materials/skills. If designs are adjustable for different depths, chances of replication are higher	+2 Component does not need to be adjusted depending on the tools used +1 Component's design needs minor modifications depending on the tools used -1 Component's design needs major modifications depending on the tools used -2 It cannot be produced with different or manual tools

Results

In Figure 23, we present a summary of the results. The summary connects each component to its related issue and the profile charts developed. In general, the results indicate that the successful adoption of RWHs as a source of potable water is mainly dependent on two aspects: the quality of the harvested water and the supply capacity of the system. The Figure also gives a first impression about replicability potential of the components. However, each profile is discussed individually next, based on the systems it belongs to.

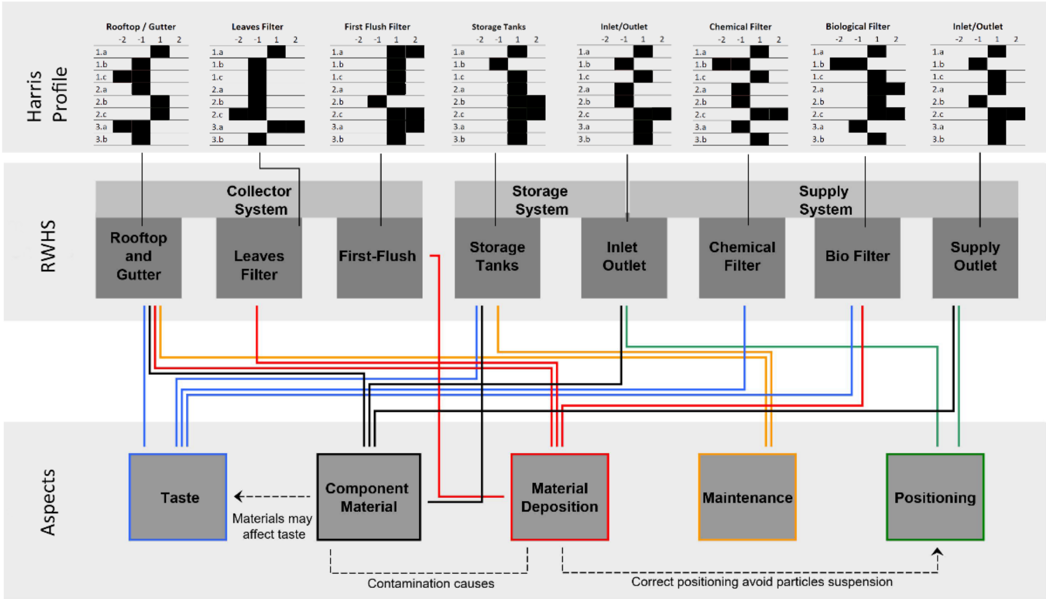

Figure 23- The resulting profile charts for each component and their relation to the RWH systems and issues. (Source: Developed by the author)

Collection

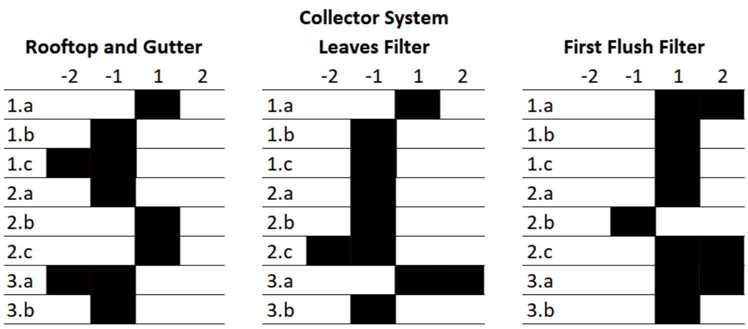

Figure 24 Profile charts of the collection system - (a) Rooftop and Gutter, (b) Leaves Filter, (c) First Flush Filter. (Source: Developed by the author)

The collection system consists of the roof, gutters, pipes, leaves filter and first flush diverter. For our analysis the components are divided between (a) roof, gutter and pipes, (b) leaves filter, (c) first flush filter and (d) outlet. Figure 24 presents the profile charts for each of the mentioned components.

The collection system is considered to be the main source of rainwater contamination, especially the roof (HAN; KI, 2010). Two types of contaminants are responsible for altering the water quality, i.e. potability, pH, taste, color and odor: deposited particles (e.g. leaves, birds faeces, chemical particles) and material components. First flush devices, filters and screens and regular maintenance of the roof are indicated as solutions to minimize the effects of material deposition at the rooftops (LYE, 2009). And the design and position of the outlet, which connects the collecting pipes to the storage tanks, is mentioned as a solution to avoid sediment resuspensions (MAGYAR et al., 2007; NGUYEN et al., 2013). Authors also indicate that the components materials contribute to physical (taste and pH) and chemical changes of the harvested water (Chang et al., 2004; Mayo and Mashauri, 1991; Morales-Pinzón et al., 2015). Other components might also contaminate the harvested water. For example, PVC pipes and outlets increase the amount of lead (Morrow et al., 2010) and copper pipes are responsible for higher concentrations of Cu in water (SIMMONS et al., 2001).

Regarding its openness potential, the rooftop and gutter components are unlikely to be included in an open design process because of its complexity (1.b) in terms of design - requiring knowledge in 2D CAD Software, familiarity with materials and rooftop structural design (1.c) - and specificity - it needs to be adapted in terms of dimensions and shape for each context (3.a). And, despite the fact that it can be produced using a high variety of materials (2.b) and standard tools (2.c), some precautions are needed in order to prevent the adoption of materials with a high potential for contamination. The filters, on the other hand, have a higher potential for openness because of standardization or easier adaptation for different contexts (3.a and 3.b). However, the leaves filter is less prone for replicability because of its functioning requirements which requires certain specific production methods such as PVC molding or 3D printing (2.a and 2.c). The first flush filters, in its turn, are more likely to be replicated once their design is relatively simpler when compared to other filters. It can also be assembled or produced using common materials (2.a), although the type of materials is restricted (2.b). Lastly, adjustments are possible without affecting its performance (3.a and 3.b) and depends on low-tech tools to be produced (2.c). It is also possible to identify examples of DIY first flush diverters in OD repositories.

Storage

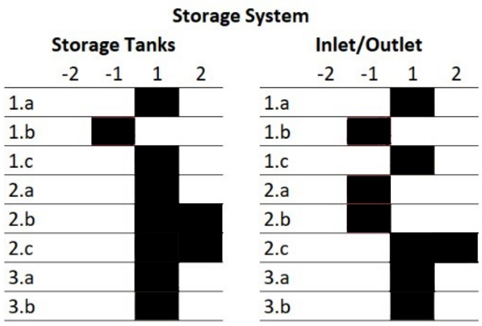

Figure 25 Profile charts of the storage system - (a) Storage Tanks, (b) Inlet and Outlet. (Source: Developed by the author)

At the storage system, contamination, cistern design and construction methods are the main topics explored in the literature. Contamination happens both because of the materials/coating processes adopted but also because of the storing length and methods. The materials used to build or coat the water tanks might alter the water characteristics affecting its odor, taste, color, pH and/or potability. Even if it does not affect water potability, the alterations make people less confident about consuming the harvested water. In addition to that, long periods of storage also increase microbial contamination (KIM et al., 2005). Constant maintenance and correct cleaning are often mentioned to minimize the chances of contamination (BURT; KEIRU, 2009), however, it demands not only training but also awareness of the risks and motivation to perform such activities (BAGUMA et al., 2010; GOMES; HELLER, 2016).

Examples of design suggestions of the storage tanks - cistern design and construction methods - are well explored. Some indicate different types of cisterns for different locations while others focus on providing instructions to build specific types of tanks using local materials. An example is the Calabash Tank (HARTUNG; HEIJEN, 2016), an optimized ferrocement tank. In addition to that, different types of tanks are described in terms of construction costs, difficulty to build, replicability and materials (RHRG, 2001).

The replicability of the storage tank has been rated as high in the Harris Profile (Figure 25), enabling either low or high technology approaches. Existing examples show that storage tanks can be of a wide range of materials - bricks, clay, concrete and other - construction methods and designs (2.a). 2D CAD drawings and instructions are enough for design replication (1.a), however, technical experience is required for modifications, e.g. structural design of the storage tanks (1.b).

The inlet/outlets components of the storage system are listed in the literature as a minor issue, mostly related to its correct positioning to prevent particles suspension in the tanks (HAN; KI, 2010; MAGYAR et al., 2007). Hence, the Harris Profile refers to the correct adjustment of those components and not their manufacturing process. The replication of improved alternatives is feasible based on 2D drawings and/or instructions (1.a) but design modifications depend on technical knowledge and water quality tests (e.g. to measure particles suspension during water inflow) (1.b and 1.c). The adoption of the design is dependent on vitamins (parts not suited for DIY production) because of the outlet/inlet pipes production process and materials (2.a and 2.b). However, the assembling process depends on standard tools, mainly manual (2.c).

Supply

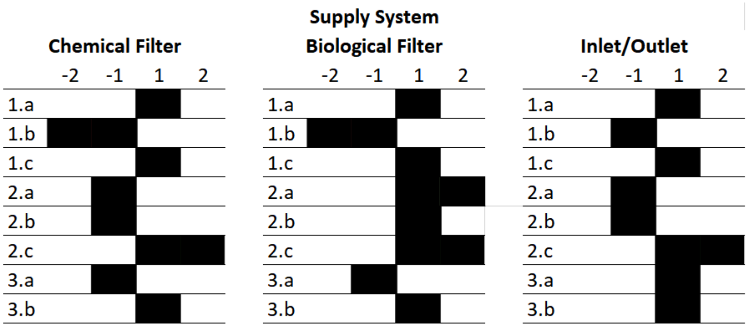

Figure 26 Profile charts of the supply system - (a) Chemical Filter, (b) Biological Filter, (c) Inlet and Outlet. (Source: Developed by the author)

The supply system corresponds to the filtering methods/processes and the inlet/outlet components.

The filters are well explored given their importance to the system effectiveness. The existence of two types of contaminants, chemical and microbiological, plus the existence of suspended particles lead to discussions about design alternatives and methods effectiveness, especially for low-tech alternatives, e.g. solar disinfection (SODIS), boiling, chlorination. However, the effectiveness of some of such methods, e.g. SODIS, is questionable once they do not meet International guidelines for water potability (ISLAM et al., 2015; NALWANGA et al., 2016). Therefore, the adoption of two complementary methods is often recommended. Fast and Slow Sand Filters are suggested for particles and microbiological filtering (THOMAS, 1998) and they consist of a low complex alternatives (OPARE, 2012). On the other hand, chemical decontamination requires more complex methods such as membrane filtration and its costs make it not suitable for poorer communities (HELMREICH; HORN, 2009).

Microbiological filters (MFs) and the chemical filters (CFs) were ranked differently in the Harris Profile. However, both types of filters are similar in terms of accessibility and transparency. Both can be reproduced using a set of drawings, instructions and manuals (1.a) but the complexity of the filtering processes and its safety standards requirements result in the need of experts for design modification and optimization (1.b). At the same time, suggestions can be made by comments, instructions and basic diagrams (1.c). Modifications and contributions to the system can be made through simple diagrams or comments but, if aimed at improving its filtering performance, they need to be evaluated through water quality tests.

In terms of self-production, the MFs were evaluated slightly better than the CFs. The reason is that there is a wide range of alternatives (2.b) for biological decontamination ranging from simple processes - boiling and SODIS - to more complex ones - sand filters (3.b). At the same time, the materials and tools needed for simpler processes are widely available (2.a and 2.c). For example, SODIS can be performed using enclosed containers and secondary treatment processes can use lemon/vinegar (AMIN; HAN, 2011) and boiling processes. On its turn, examples for chemical treatment indicate a higher complex process, although it is also replicable under a DIY approach (3.b). The difference lies in fewer existing alternatives (2.b) and less alternatives of treatment processes (2.a). However, when the components are available, CF can be assembled using standard tools (2.c). Finally, both BF and CF are limited in terms of flexibility (3.a) because changes might have a negative impact on systems' performance. Hence, quality control is an important factor to be considered in OD processes.

The inlet/outlet components of the supply system were ranked equally as the inlet/outlet components of the storage system given that some of the components are the same and existing concerns are related to the correct positioning of the outlet to prevent particles flow with the supplied water.

Discussion

In this study we explored to which extent replication of physical artefacts is affected by OD. For that purpose, we adopted the RWHs as the object of our analysis and identified the main components of the system that are important for its effectiveness. OD design is a potential alternative to make technology, such as RWHs, more easily available for poor communities. However, as the profile charts we developed indicate, there are certain limitations to that, which we introduce next with possible pathways to improve replicability in OD.

OD beyond digital development

Although the idea of sharing designs and instructions for building physical artefacts precedes the rise of online communities, the OD phenomena and the recent trends in the DIY movement are a direct consequence of recent advances in information and communication technologies. Hence, the digital sphere is a natural place for the collaborative development of OD objects and design sharing. The possibility of remote collaboration enhances the possibility enthusiasts and users' participation in design processes accordingly to their field of expertise, by means of modularization. In this sense, knowledge diversity helps innovation processes (FREY; LÜTHJE; HAAG, 2011; SHAH, 2005) and turns OD a viable pathway for the development of complex objects. Examples of complexity in OD vary from medical products (OpenBionics and Openprosthetics), computer gardening tools (OpenAg), manufacturing tools (3D printers and CNC), furniture (OpenDesk) and housing modules (Wikihouse).

However, we point out that simpler objects/products (e.g. first-flush filters), in opposition to more complex ones (e.g. chemical filters), tend to facilitate openness for specific reasons. First, it demands less skills in digital tools for collaboration and design modification, e.g. design platforms structure and modeling tools. Hence, it enables collaboration from users which might have less technical knowledge but are aware of needs related to the local context - providing inputs about manufacturing restrictions and material availability - for instance. Second, it increases the possibility of self-production, through the use of manual tools instead of digital manufacturing processes, and demands less vitamins. Finally, it allows standardization or requires minor design modifications for adjustment in different locations. It is also important to note that the same component can be designed assuming different depths of complexity, e.g. can be designed for digital manufacturing or using conventional hand tools. Encouraging OD processes to consider DIY design principles is important for enhancing replicability by a wide non-specialist public. Although the DIY approach already indicates some concern regarding material availability, e.g. using materials that are to-hand (BONVOISIN; PRENDEVILLE, 2017), we also consider of high importance to incorporate to OD a "design for frugality" mindset, including concerns related to (i) product robustness to deal with infrastructure shortcomings, (ii) affordability for most of the society and (iii) users' low skills and/or illiteracy (TIWARI; HERSTATT, 2012).

Distributed Manufacturing in Mobile Factories

The combination of the profile charts indicates that some specific issues concerning the adoption of RWHs are likely to be addressed by OD because of their replication potential. Water safety can benefit from first-flush filters, biological filtering processes and adjustment in positioning the inlet/outlet components. It is possible, therefore, to envision the adoption of RWHs as decentralized infrastructures for access to water. In the same direction, we speculate the possibility of OD as a viable alternative to address local issues not only related to water access, our object of analysis. Access to basic infrastructure services, e.g. sanitation and energy, could be improved if a decentralized approach was adopted by communities/individual households.

However, as our results also indicate, replication in OD is limited to the complexity of the solution based on the expertise and tools needed, materials and components availability. Distributed manufacturing - through micro-factories, Fablabs and MakerSpaces - is often argued to democratize design and enable users to manufacture, for example, products designed anywhere in the world and shared in online platforms (FOX, 2014; KOSTAKIS et al., 2015). That enhances the potential for replication of more complex designs. The bottleneck for such spaces is limited access to resources, economic and human, faced by locations which lack access to basic needs. Furthermore, economic viability of such spaces depends on the number of its potential users. Therefore, fixed digital manufacturing spaces are unlikely to be installed in specific conditions. One possible alternative is the deployment of a mobile-factory concept (FOX, 2014), already adopted in the construction industry (RAUCH; MATT; DALLASEGA, 2015). This make-and-move approach optimizes investment resources and enable experts in manufacturing technologies to either help local users to produce their products or to teach the basics for operating digital manufacturing tools, for instance. Examples of similar approaches have been tested to provide technology education in different locations, e.g. CodeBus Africa (BAKIĆ et al., 2018).

Safety and Liability

Most of the issues reported in the literature, as seen in Table 15, are related to the quality of the harvested water. Safety, therefore, plays an important role in OD processes and it is particularly important in two moments: The design phase and the manufacturing/operation phase. It has been argued that one of the benefits of collaborative development processes, e.g. OpenSource and Open Innovation, is the possibility of testing development versions during early stages which also optimizes error finding and feedback (LAKHANI; PANETTA, 2007; LAKHANI; WOLF, 2003). Testing physical artefacts demands the production of prototypes (or simulation) which is relatively more complex than testing OS software. Nonetheless, it is also arguable that one positive aspect of OD is that users with access to manufacturing tools and quality test equipment can perform the evaluation of design alternatives proposed by users without access to the required tools.

Regarding the manufacturing and operating stage, uncertainty about the quality of the harvested water might prevent users to consume or adopt RWHs (MANKAD; TAPSUWAN, 2011). In addition to that, it is not possible to assure the quality of the harvested water because of possible issues during the manufacturing process, operation or other externalities. For example, although SODIS is argued to be an effective way to reduce microbial contamination, some studies show that its efficacy is not always a certainty (ISLAM et al., 2015). Therefore, water quality tests are recommended to assess it but the costs of the instrumentation needed might be unviable for certain locations (WIJNEN; ANZALONE; PEARCE, 2014). There is, however, another application for OD processes: the development of scientific tools. Open-Source water quality tests have already been proposed costing between 7.5 and 15 times less than commercial tools (WIJNEN; ANZALONE; PEARCE, 2014). This is an important aspect to be considered in OD projects: Although the projects are usually tested and evaluated by the project collaborators, design replication can substantially benefit from ways for self-evaluating the quality of the manufactured product.

Design Parameters

Although the System Standards domain was not part of our analysis, it plays a fundamental role on RWHs efficiency. Existing studies show that some installed RWHs do not meet the recommended volume of water for drinking and basic hygiene defined by the World Health Organization (WHO) (ARKU et al., 2015). For example, the correct dimensioning of the system depends on a number of variables related to number of residents, rooftop dimensions and rainfall volume (GHISI, 2010). It is also dependent on optimum costs alternatives (BOCANEGRA-MARTÍNEZ et al., 2014). These variables are, as expected, different from location to location. Consequently, its components, specially the storage tanks, need to be adjusted accordingly to these variables. In this case, replication is directly linked to the flexibility capacity of the component. In other words, the easier it is to adapt a design to local conditions, the easier it is to replicate it. Two approaches can be considered. The first refers to the possible development of Open Source tools/applications for correct dimensioning of the system. We understand that it could help users to estimate, for example, the correct size of the components they need and the volume of harvested water during the different seasons. Campisano et al., (2017), describes 11 tools for estimating and evaluating water efficiency in RWH systems and indicates that the tools are becoming more detailed and complex. Some are already freely distributed by its developers - e.g. NETUNO (VIEIRA; GHISI, 2016) but might be limited to specific locations and climate conditions.

The second approach consists on the adoption of parametric design in OD processes to optimize design adjustments. The possibility of parametrizing a high number of variables increases the complexity of the physical solution - providing a better solution - without affecting the way users interact with it at the development stage. For example, while it might be important to a user to adjust the storage tank dimensions based on his needs, he might not be aware about the structural consequences of such modifications. Parametric design could, therefore, prevent that modifications to the design affect its functionality. We understand it to be an important feature to be incorporated in OD processes. In fact, it is already adopted in OD projects with a high intent for customization. For example, the Wren language, developed for Wikihouse, is a parametric code aimed at the development of a flexible construction system, less complexity to adapt the design and provide end users with the capacity to self-modify it (PRIAVOLOU; NIAROS, 2019).

Conclusion

The aim of this study was to explore the challenges of OD for replicability of different components of the same system and comment on possible pathways to overcome such limitations. For that purpose, we defined the RWHs as our research object and identified the main issues/components related to its adoption. The components were then evaluated regarding their replicability potential for collaborative development and adoption by final users.

The analysis results indicated that some design limitations which affect the correct functioning of a system can be overcome through OD processes and its outcomes (physical artefacts). In the case of RWHs, for instance, first-flush diverters have a high potential to be replicated and, therefore, are more likely to be successfully in OD processes. At the same time, other components can be potentially harder to replicate given specific limitations. Our observations indicate four main challenges that need to be considered. There is a need to (1) incorporate a design-for-frugality mindset to the development of physical artefacts, (2) stimulate the development of mobile micro-factories, through OD manufacturing technologies, (3) consider ways to enable users to self-evaluate the liability and safety of the OD artefacts and, finally, (4) adopt parametric solutions to improve design customization.

We understand the results can benefit OD enthusiasts to consider new aspects during the development of physical artefacts, especially those aimed at tackling sustainability challenges in poorer communities. It also indicates possible pathways to enable the adoption of OD solutions in places that lack access to technologies and high-skilled professionals by implementing, for instance, mobile micro-factories.

The subjectivity of the evaluation process is a possible limitation of this study and the principles adopted might not represent the full range of possible criteria for evaluation. Therefore, of particular interest for future research will be the exploration of each one of the challenges we highlight with a less generic approach in order to fill possible gaps - using a broader range of cases, for instance. By addressing them individually, new perspectives and solutions/pathways can emerge. For example, we find it very important to understand how design safety and liability could be addressed in OD processes, especially when authorship is diffuse such as in open collaborative processes.

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5.4 RQ4 - Measuring Open Design Communities. What can we learn from mining data in collaboration Forums?

Abstract

Open collaborative development and transparent design processes are often associated to the concept of Open Design (OD). Studies in remote collaborative processes are still recent and a wide number of aspects of OD remain unclear. As a contribution, this study explores the extent of knowledge we can create about an OD project from mining data in collaboration platforms. As our research object, we selected the Open Agriculture Initiative. Data was mined from its online forum, and Github, a development platform. Social Network Analysis (SNA) and topic modeling techniques were used to explore four research questions we proposed. We comment on these questions highlighting differences between both platforms, stakeholders participation and personal interests, community changes over time, activity volume and latent topics. Finally, we conclude by indicating possible pathways to the investigation of OD as an emergent phenomenon by using data mining techniques.

Introduction

Open Design (OD) enthusiasts and researchers often define it as a collaborative development process which outcomes are publicly shared for anyone to produce/use, study, modify and distribute them (AITAMURTO; HOLLAND; HUSSAIN, 2015; BOISSEAU; OMHOVER; BOUCHARD, 2018). It is also accepted that openness, as a metric, is gradual and multifactorial. It means that OD projects can be more or less open based on how collaborative/accessible is the development process, how robust and available are the outcomes (source documentation) and how replicable it is (BALKA;

RAASCH; HERSTATT, 2014; BONVOISIN; MIES, 2018). Collaboration, therefore, is one of the major critical aspects for achieving fully open projects. Previous studies have mapped different online collaboration processes in Open Source Software (OSS) development (LERNER; TIROLE, 2003; OSTERLOH; ROTA, 2007; VON HIPPEL; KROGH, 2003) and Wiki communities (AALTONEN; SEILER, 2016) in order to understand it. More recently, studies in Open Source Hardware and OD have also explored the structure of these communities and the development processes by using both quantitative and qualitative approaches, such as interviews (FERDINAND, 2018; MALINEN et al., 2010) participant observations (MACUL; ROZENFELD, 2015) and data mining of online platforms, such as Github (BONVOISIN et al., 2018; MENICHINELLI, 2017).

Until now, studies using data mining techniques have focused mainly in online repositories. A well-known example of this type of repository is Github. Github enables not only users to perform commits (revision/contribution) to project files but also keeps track of the version history. These studies have been able to provide interesting information about the interactions between users, the influence and importance of actors, and the activity volume (MENICHINELLI, 2017). However, one hurdle of this approach is that Github *"does not capture all product development activity happening in a project."* (BONVOISIN et al., 2018). From our perspective, it also does not evidence an important aspect of such communities: Communication. We consider that Github has a limited structure for users to communicate, being limited to issues reports and commits description. In this sense, it is possible to identify OD projects that adopt both Github for the development process and a different type of platform, especially Forums, for communication between users. Some examples of these projects are listed next: (i) RepRap, an OS 3d printer, (ii) OpenAgriculture Foundation, aimed at the development of Personal Food Computers (PFCs), (iii) OpenROV, a remote-operated underwater robot and (iv) Maslow, a large CNC cutting machine. We consider that in the study of the OD phenomena, it is important to understand, not only the actual development process, e.g. revisioning files, but also the communication process of a community.

In this study, we aimed at two particular outputs. First, we wanted to understand what kind of knowledge we can create from mining data from communication platforms (Forums) of a particular project. We opted for the OpenAgriculture Foundation (OpenAg) project as our object of analysis. Besides having users' activities in both types of platforms (Github and the Forum), the reasons for choosing this particular case are related to a bigger research project which aims to investigate whether OD can help addressing global challenges with local implications. From our perspective, OpenAg is directly linked to food supply. A secondary output refers to what kind of assumptions can we make about this particular project, based on the knowledge we build from data mining processes. For this purpose, we outline four questions to guide our study:

RQ4a: Do OpenAg and Github perform equally in terms of collaboration and decision-making processes?

RQ4b: Do users' importance and network structure change over time? Can we identify the most important reasons for users joining the project?

RQ4c: Why do single-time users participate in the community and how do they affect the activity volume?

RQ4d: Can we identify important discussion topics based on Topic Modeling tools?

The following sections (1.2 and 1.3) provide a general overview of two particular tools we adopted in this study: Social Network Analysis (SNA) and Natural Language Processing (NLP). Following that, in Section 2, we present the methods we adopted to obtain the data we needed and to perform the analysis. Section 3 presents the results for each one of the RQs which are then discussed in Section 4. We also highlight the limiting factors of our study and propose new research questions for further investigation (4.2). The main outcomes of this article are related to the possibilities that mining techniques have for social network analysis. By addressing one particular forum, we introduce a new perspective to understand the communication processes outside project development platforms (Github). The results confirm, for example, that the type of communication that the forum enables, enhances the democratization of the project by enabling users from different levels of knowledge to participate, exchange ideas and solve particular issues. From a practical perspective, the results offer valuable information for project "owners", i.e. those who initiate a particular OD project, to identify the health of their community, trend topics and possibly, increase user's participation.

Social Network Analysis (SNA)

Although SNA has gained attention in the last few years given the rise of Information and Communication Technologies (ICTs), its use can be traced back to the 1930s' with works in social psychology, urban sociology and mathematics (FREDERICKS; DURLAND, 2005). The sociogram, created by the social psychologist Moreno, was built based on topological notions from graph theory (BARNES, 1969) consisting of a method for representing social relationships as points and lines. More recently, SNA has been applied to a wide range to topics, such as political polarization in social media/networks (GRUZD; ROY, 2014), consumer behavior (SITKO-LUTEK et al., 2010) and groups behavior in sports (LUSHER; ROBINS; KREMER, 2010). Besides that, it has been adopted to understand user interactions in OS platforms (SHEN; MONGE, 2011), investigate the evolution of networks and its relation to product development (LE; PANCHAL, 2012), investigate transparency and activity volume (BONVOISIN et al., 2018) and map the geographical distribution of users (HELLER et al., 2011).

Early studies have also identified basic structural characteristics of networks such as density, centrality and isolation (FREDERICKS; DURLAND, 2005). These different metrics are used in graph theory and are chosen based on the phenomena one wants to investigate. They fall into two categories. First, global measures indicate the global properties of a network and are, therefore, represented by a single value. Second, nodal measures refer to the properties of the nodes and have individual values for each node (MIJALKOV et al., 2017). In the study proposed by Bonvoisin et al. (2018), for instance, the authors computed the *global centrality indexes* - the variation in the relative importance of all nodes in a graph, and the *clustering indexes* - the degree to which nodes tend to cluster together. Other measures can (i) indicate the importance of each node in the community, e.g. *Eigenvector Centrality*, (ii) the extent to which a graph can be divided into clear categories, e.g. *Modularity*; and (iii) the number of connections each node has, e.g. *Degree.*

Natural Language Processing (NLP)

The history of NLP traces back to computer translation experiments during the WWII in the 1940s. It refers to the use of "(...) *computational techniques for analyzing and representing naturally occurring texts at one or more levels of linguistic analysis."* (LIDDY, 2001). One of the approaches used in NLP is topic modeling, a statistical method for identifying latent topics across a set of documents. Different techniques have been developed to perform topic modeling of documents, especially after the emergence of electronic documents, e.g. books, emails and reports. Dumais et al. (1988), for instance, introduced the latent semantic indexing (LSI) approach with the aim of improving information retrieval by automatically organizing textual documents into latent topics. Later, Blei et al. (2003) proposed the latent dirichlet allocation (LDA) to improve previous techniques, such as the LSI. One of the major benefits of the LDA approach is that it is based on probabilistic modeling, which means that textual documents can be represented (probabilistically) by different latent topics. Other examples of techniques are the probabilistic LSI (pLSI) (HOFMANN, 1999) and hierarchical dirichlet process (HDP)(TEH et al., 2005).

The applications of such methods are vast. Authors have used topic modeling to investigate differences between similar research concepts (D'AMATO et al., 2017) and identify research trends (SUGIMOTO et al., 2011). Others applied it on newspapers textual data to identify major topics over time (NELSON, 2010; TORGET; YANG; MIHALCEA, 2011) and study discussion forums (EZEN-CAN et al., 2015). In OS studies, topic modeling has been applied mainly to categorize bug reports (SOMASUNDARAM; MURPHY, 2012), identify duplicate reports (HINDLE; ALIPOUR; STROULIA, 2016), identify informal project requirements (VLAS; ROBINSON, 2012) and, finally, classify users requests (LI et al., 2018).

Methods and Tools

The OpenAgriculture Initiative (OpenAg) is an Open Source community initiated at the MIT Media Lab in 2015. The project aims at *"building an ecosystem of food technologies to create healthier, more engaging and more inventive food systems"*. The Initiative has different projects related to the optimization of the crops in controlled environments and the design of Food Growing Platforms. The Personal Food Computer (PFC) is an example of such platforms. It consists of *"a tabletop-sized, controlled environment agriculture technology platform that uses robotic systems to control and monitor climate, energy, and plant growth inside of a specialized growing chamber."* Since 2015, five versions of the PFC have been developed by the community and the last release - version PFC 3.0 - was made in October, 2018. The Initiative has also developed an educational version of the PFC for learning purposes.

Data Extraction

Data extraction was performed for two platforms: Github and the OpenAg Forum. Github is mostly used for active modifications in the source documentation of the project while the Forum is used by users to share ideas and information, present their own work and post issues they may face. For both platforms, we adopted mining techniques using either existing Python scripts or self-developed scripts which we will present next.

Github Data extraction

Raw data extraction was performed using GitHub's API queried through python scripts developed by Bonvoisin (2018) and released under an OSS license. The scripts extract metadata related to changes history of all repositories of the same project and all corresponding forks. The metadata provides information about changes in a repository file (commit), 'who' performed the changes (committer), when it was updated and what previous commit it is related to. An example of the data extraction structure is presented in Figure 27. Each project may present a number (n) of different repositories. The repositories contain the files(n) and stores each file's revision history. In the example we provide, files 1 and 2 were changed by three users and a diverging branch was created to file 1, indicating that 2 users (C and D) performed different modifications after B.

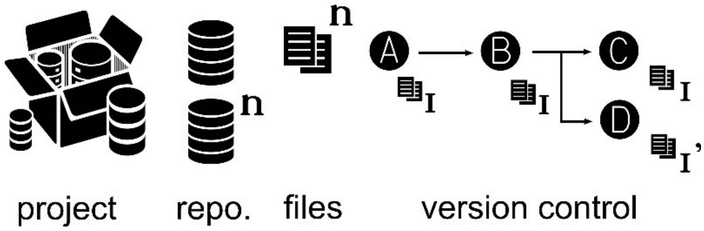

Figure 27 - Illustration of the information provided by mining the GitHub API. (Source: Developed by the author based on Bonvoisin et al., 2018)

For the OpenAg project we mined the 44 existing repositories (23 archived and 21 open by the time of the data extraction). We did not limit the repositories to those that are related to hardware components because we understand that both the software and hardware are important for the correct functioning of the OpenAg platforms and that users may contribute to different repositories as well.

OpenAg Forum Data extraction

As for the OpenAg Forum, data extraction was performed using web scraping techniques. We developed four different scripts based on **scrapy**[10], a python module for extracting the data we needed. Scripts were released under an OS license in an online repository (Appendix C) (FREIRE, 2019). First, we collected all existing topics from April, 2016 to September, 2019 and their corresponding links. Second, for each topic, we collected data related to (1) the topic creator, (2) repliers, (3) textual comments, (4) replies dates and (5) the topic category, e.g., Hardware or Help. Third and fourth, we obtained users data to explore (1) their affiliation and (2) their activity on the page (first and last appearance). In the case of the Forum, collaboration between users were less evident than in Github. For that reason, we considered two possibilities for defining collaboration (Figure 28). In the first case (left), we considered that interaction occurred when one user's comment followed someone else's comment within the same topic (A→B,B→C,C→D). A possible limitation to that scenario is that comments might not necessarily be related to each other and that the same user might comment more than once in a row. In the second case, we considered that interaction occurred only between the creator of a topic and a user that commented on his topic (A→B, A→C, A→D). In this case, a possible limitation is that the number of replies does not necessarily relates to the importance of the topic. For example, the **"Twitter/Instagram (add yours)"**

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[10] The python library is available at https://scrapy.org

Topic had 57 replies and the **“16 years old kid from Czech Republic is trying to build Food Computer”** Topic had 7 replies at the moment that data was extracted. Given the content of the topics, we considered that limiting interaction to the number of replies a topic has could provide misleading results. Besides that, we identified that after some replies, some comments were not necessarily linked to the topic but to following comments. Finally, after a comparison between the two case, we selected the first one to proceed with our analysis.

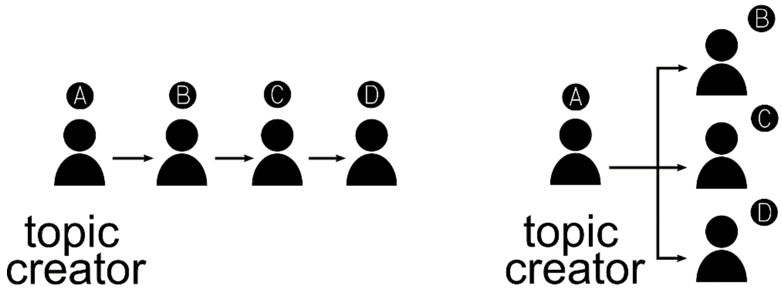

Figure 28 - Two possible cases for structuring the data from the Forum. (Source: Developed by the author)

At the moment of the data mining, the forum had 1866 subscribed users. Of that amount, 757 users participated at least once in the Forum and 97 had a description in their profile that enabled us to trace back their affiliation. Following that, we calculated the eigenvector centrality for each user and extra manual work was performed to identify the affiliation of users with a high centrality. Briefly speaking, the Eigenvector Centrality measures the importance of a node in a network. Next section describes the measurement classification we adopted. Based on initial explorations, we applied a set of keywords to explore the affiliation of the top 100 users. Finally, we managed to classify other 41 users. The keywords and the users’ classification are presented below:

- Keywords: “work”, “study”, “student”, “teacher”, “company”, “hobby”, “I am”, “like” and “school”
- Classification:

- Enthusiast = Users that show appreciation for the DIY-movement, open-source, open innovation or present themselves as hobbyists, and are not classified as entrepreneurs, educators or students and OpenAg Members.
- Entrepreneur = Users that present themselves as a founder or interested in founding a company specialized or not to the project in question. It also considers employees that are directly interested in the topic because of professional purposes.
- Education = High School, Undergraduate and Master Students, researchers and educators.
- OpenAg Member = Active or former members of the OpenAg.

Network analysis and metrics

We adopted the Open Graph Viz Platform (Gephi[11]) for network visualization and social network analysis (SNA). We structured the data based on the platform requirements, identifying the users as *source* and *target,* their Ids and dates. Interaction between users is defined as either the subsequent reply at the same forum topic and the edition of the same file of a GitHub repository.

For the OpenAg Forum, we structured the data in a period of four months according to the time-period presented in Table 17. Next, we developed undirected graphs for the first period and the following ones using cumulative frequency, e.g. the third graph corresponds to the summation of the first, second and third periods. Yifan Hu's layout algorithm was used to represent the time-lapse of the network for the periods 1-10. The algorithm is force-directed, i.e. it uses attraction and repulsion forces acting between the bodies of a system (HU, 2005), enabling some (but limited) inferences about

[11] The platform can be downloaded from https://gephi.org

the visual results. For that reason, we compared the final visual representation of the network using Yifan Hu's layout with other graph generation techniques.

Table 17 – Analysis timeframes for OpenAg data.

Period	Time_start	Time_end
1	20/04/2016	21/08/2016
2	20/04/2016	21/12/2016
3	20/04/2016	21/04/2017
4	20/04/2016	21/08/2017
5	20/04/2016	21/12/2017
6	20/04/2016	21/04/2018
7	20/04/2016	21/08/2018
8	20/04/2016	21/12/2018
9	20/04/2016	21/04/2019
10	20/04/2016	21/08/2019

In addition to the network visualization, other metrics can be used to understand and classify the network evolution during the timeframe we defined. For that reason, we calculated two topological indicators for each timeframe:

- The *Eigenvector Centrality (EC)* measures the influence of a node in a network. Differently from the simple *degree centrality*, it considers not only the number of connections a node has but also its importance to the network. The rationale is that connecting to nodes that are more important in a network lends one node to be more influential than if it were connected to "weaker" nodes. We used the EC to evaluate how user's centrality may change during a period of time. For that purpose, we compared the initial EC values (timeframe = 1) to the following EC values (timeframes = 2-->10).

- *Modularity* (BLONDEL et al., 2008) extracts the different communities of a given weighted network based on the repetition of two iterative phases. First, it assigns a different community to each node and, second, it evaluates the gain of modularity by changing the community each node belongs to. The analysis stops once the maximum modularity is achieved for each one of the nodes. We calculated the modularity values for each timeframe. And, in order to explore the dynamic behavior of the network, we applied only the last modularity calculation (timeframe = 10) to the network visualization of all timeframes.

We also generated the Github network based on the *Yifan Hu's algorithm* and calculated the EG and Modularity values in order to compare with the results of the OpenAg Forum. We generated a single network based on the activity period ranging from April 2016 to September, 2019.

Activity Volume and Users contribution

We calculated the activity volume for the OpenAg Forum and Github considering the number of replies and file changes as reference units. Although both are not numerically comparable, such calculations enable us to observe whether higher activity volumes in one platform reflected in another platform and if the activity volume tended to increase or decrease during the period of analysis.

We also managed to associate the users from OpenAg Forum to the Github users. Our objective was to identify whether the participant activity in one platform also reflected in the other one. Although we did not manage to identify all corresponding users, we managed to associate 138 users, most of which presented a high activity level. Finally, we linked the user's affiliation and explored their role in the activity of the OpenAg community.

Topic modeling

Latent Dirichlet Allocation (LDA) is an effective method for classifying and clustering textual data (topic modeling) of a large number of documents. It identifies underlying topics in texts (documents) and describes them as a distribution over terms and calculates the probabilities of a document to belong to each one of the different topics, i.e. each document might be associated to one or more topics. LDA has been successfully applied for large texts, such as in bibliometric analysis (D'AMATO et al., 2017), however, it has also been proved effective for shorter texts such as in Twitter (HONG; DAVISON, 2010). In order to process the LDA analysis, one must attribute a number of desired topics. Given that different topic numbers affect the quality of the model, it is important to evaluate the quality for different possibilities. By measuring the topic coherence for different number of topics (range=2-40), we were able to define the criteria of 8 topics to our modeling (Table 18).

Table 18 - Optimal number of topics for LDA analysis of the Forum content.

Topics	Coherence scores for a series of 10 analyses										Average scores
2	0.3397	0.3537	0.3691	0.3724	0.3747	0.3885	0.3905	0.3812	0.3622	0.4254	0.3757
4	0.3724	0.3138	0.3803	0.3763	0.3996	0.3822	0.3895	0.3899	0.4180	0.3769	0.3799
6	0.3586	0.3505	0.3680	0.3986	0.4066	0.4321	0.3950	0.4011	0.3831	0.3674	0.3861
8	0.3295	0.3753	0.3740	0.4075	0.3945	0.4273	0.4464	0.4502	0.4274	0.3367	0.3969
10	0.4046	0.3954	0.3646	0.3673	0.4332	0.3769	0.4042	0.3798	0.3904	0.3408	0.3857
12	0.3721	0.3563	0.3697	0.3792	0.3627	0.3780	0.4275	0.3867	0.4173	0.3521	0.3802
14	0.3474	0.3676	0.3786	0.3941	0.3991	0.3856	0.3944	0.4051	0.3816	0.3586	0.3812
16	0.3807	0.3646	0.3628	0.3816	0.3951	0.3996	0.3977	0.4025	0.3747	0.3469	0.3806
18	0.3376	0.3714	0.3760	0.3751	0.3762	0.3780	0.3808	0.4000	0.4062	0.3397	0.3741
20	0.3717	0.3679	0.3804	0.3641	0.3616	0.3960	0.3898	0.3863	0.3965	0.3338	0.3748
22	0.3703	0.3525	0.3902	0.3908	0.3632	0.3708	0.3861	0.3938	0.3899	0.3151	0.3723
24	0.3564	0.3566	0.3780	0.3554	0.3989	0.3701	0.3924	0.4248	0.4018	0.3277	0.3762
26	0.3608	0.3584	0.3762	0.4020	0.3782	0.3824	0.3830	0.4005	0.3960	0.3460	0.3783
28	0.3591	0.3748	0.3965	0.3771	0.3799	0.3981	0.3834	0.3871	0.4122	0.3383	0.3807
30	0.3762	0.3684	0.3911	0.3837	0.3656	0.3772	0.3803	0.3951	0.3849	0.3083	0.3731
32	0.3593	0.3693	0.3787	0.3694	0.3711	0.3651	0.3722	0.3877	0.4049	0.3341	0.3712
34	0.3855	0.3638	0.3924	0.3912	0.3740	0.3799	0.3771	0.3830	0.3920	0.3429	0.3782
36	0.3866	0.3718	0.3901	0.3867	0.3813	0.3749	0.3760	0.4025	0.4026	0.3202	0.3793
38	0.3723	0.3581	0.4022	0.3908	0.3675	0.3545	0.3914	0.3911	0.3746	0.3464	0.3749

We applied the LDA to the text content (5832 posts with textual content) mined from the OpenAg Forum. Several analyses were performed before we could achieve a coherence score higher than the average we found previously (0.3969). Textual processing methods were applied to (a) segment each reply content to a list of words (tokenization), (b) group together the inflected forms of a word (lemmatization), (c) remove punctuation and irrelevant words (stop words) and (d) associate each reply content to a document. After performing the LDA, we evaluated the topic distribution for each document and compared the results to the corresponding textual content of the forum (replies).

Results

RQ4a: Do OpenAg and Github perform equally in terms of collaboration and decision-making processes?

Figure 29 shows the percentage (of the Total) of comments in the OpenAg Forum and the percentage (of the Total) of commits in GitHub as a function of time. It indicates a tendency of the activity volume of both platforms to decrease over the whole period, from April-16 to August-19. However, we cannot confirm that the activity level between the platforms is correlate during the same period of time, e.g. from August-17 to January-18 the platforms presented opposite behavior.

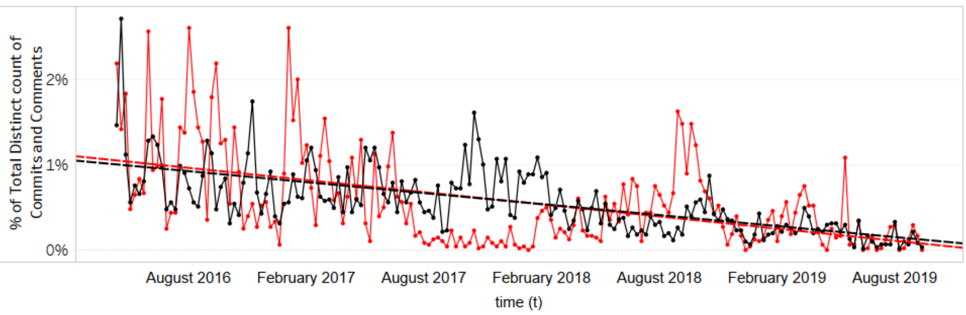

Figure 29 - Activity volume in GitHub (red) and OpenAg Forum (black) from April, 2016 to September, 2019 as a percentage of the total volume of commits and comments. (Source: Developed by the author)

Of the total of 1851 registered users, we considered only those users who had posts in the Forum, totalizing 936. Out of that total of active users, 471 (50,3%) had either one or two posts in the community and were responsible for 897 posts (15,4% of 5832). On the other hand, as Figure 30 indicates, 70 users (8,45%) were responsible for 2922 posts (50,12%). Regarding Github, 78 users had performed "*commits*" to the project. Tracing the affiliation of the users was slightly more complicated than in the OpenAg forum, therefore we could only identify 12 of them. However, we managed to identify that 39 users (50% of the total) were responsible for 99% of the commits in the project and 6 OpenAg members committed 69,37% of the contributions to the project. This number contrasts with the number we found for the Forum, showing that official members were more likely to perform changes to the project than other types of users.

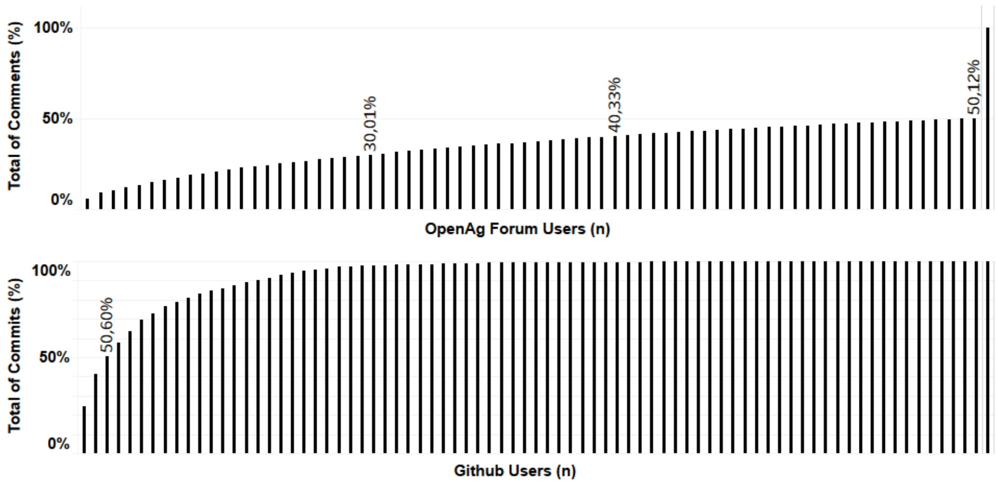

Figure 30 - Percent of Total Running of posts in OpenAg Forum (top) and commits in OpenAg Github page (bottom) for each user. The view excludes users with no posts or commits. (Source: Developed by the author)

We were able to trace the affiliation of 56 users out of the top 70 active users in OpenAg from which 5 are associated to the Educational sector, 10 are/were part of the OpenAg team, 21 are enthusiasts and 20 are entrepreneurs. If we consider that the OpenAg team is also part of the educational sector (since it was hosted at the MIT), the numbers indicate a similar distribution between the type of users in the community. Besides the 56 users (out of 70), we also traced the affiliation of other 82 users (totalizing 138 users), either because they presented this info in their profile or because it was explicit in the posts. Figure 31 shows the distribution of those users according to the affiliation type we assigned. Of the total (n=138), we classified 29 users as education (EDU), 17 as OpenAg members (OAM), 52 as enthusiasts (ENTH) and 40 users as entrepreneurs (ENTR). These users were responsible for 2966 posts, representing 16,17% of the total users and 50,8% of the posts we mined (2962 of 5832). Individually, each group represented 4,3% (EDU), 8,50% (OAM), 18,35 %(ENTH) and 19,70% (ENTR) of the total number of posts.

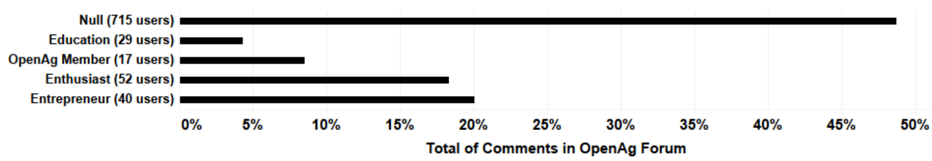

Figure 31 - Total of comments of users with mapped affiliation as a percentage of the total. (Source: Developed by the author)

The Github network shows a well-defined cluster containing the most important nodes, considering its connectivity (EC > 0.40, Figure 32 (A)). The OpenAg Members are also attracted to the main core, an expected result given their activity level at Github. On the other hand, the OpenAg Forum network (Figure 33) indicates as less centralized structure showing that the attraction forces between the most important nodes (EC > 0.40) are weaker. The diversity of the community is expressed by the distribution of the important nodes having representatives of all types (EDU, OAM, ENTH, ENTR). It is also important to note that the two most important nodes from the entrepreneur (Ev=1.0) and enthusiast (Ev=0.61) groups.

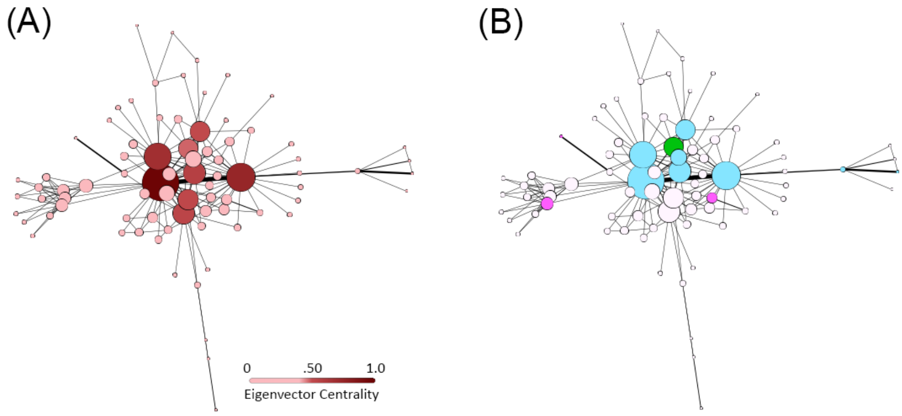

Figure 32 - Network structure of the GitHub community indicating the Eigenvector values (A) and the user's affiliation (B), which are represented as light blue (OpenAg Members), green (Education), magenta (Enthusiasts). (Source: Developed by the author)

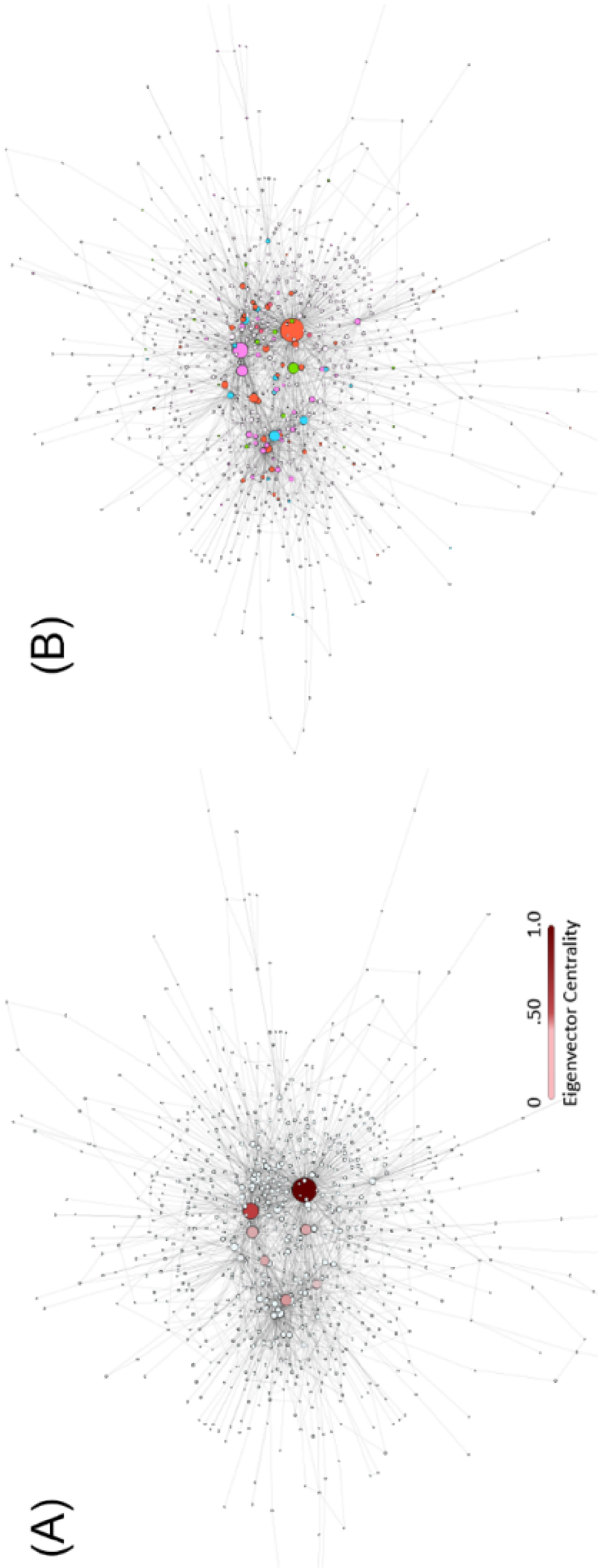

Figure 33 – (See Appendix D) Network structure of the OpenAg Forum community indicating the Eigenvector values (A) and the user's affiliation (B), which are represented as light blue (OpenAg Members), green (Education), magenta (Enthusiasts) and orange (Entrepreneurs). (Source: Developed by the author)

RQ4b: Do users' importance and network structure change over time? Can we identify the most important users' reasons for joining the project?

Figure 34 and Figure 35 present the network evolution of the OpenAg Forum based on the time series described in Section 2.2. The sequence illustrates the evolution of the network and the EC values' changes each user has (node size). The initial time frames indicate (ts=1, ts=2, ts=3) that the community started with a single strong core including the most important nodes. As time passes (ts=4, ts=5) the initial structure changes into a less compact one - gaining new cores - and other users become more important, changing the EC values distribution. Finally, the following time frames (ts=6 → ts=10) indicate the stability of this process observed in ts=4 and ts=5, i.e. the initial importance of users migrate and the network becomes even less compact. The less compact structure reflects the consolidation of new clusters. In Figure 36, these changes of users' importance are highlighted. It shows the distribution of the EC values for all periods in comparison to the values found in ts=1. Although we cannot confirm the changes for all users, it is possible to see that those with very high EC values in the beginning of the analysis did lose their importance over time, whilst others gained importance.

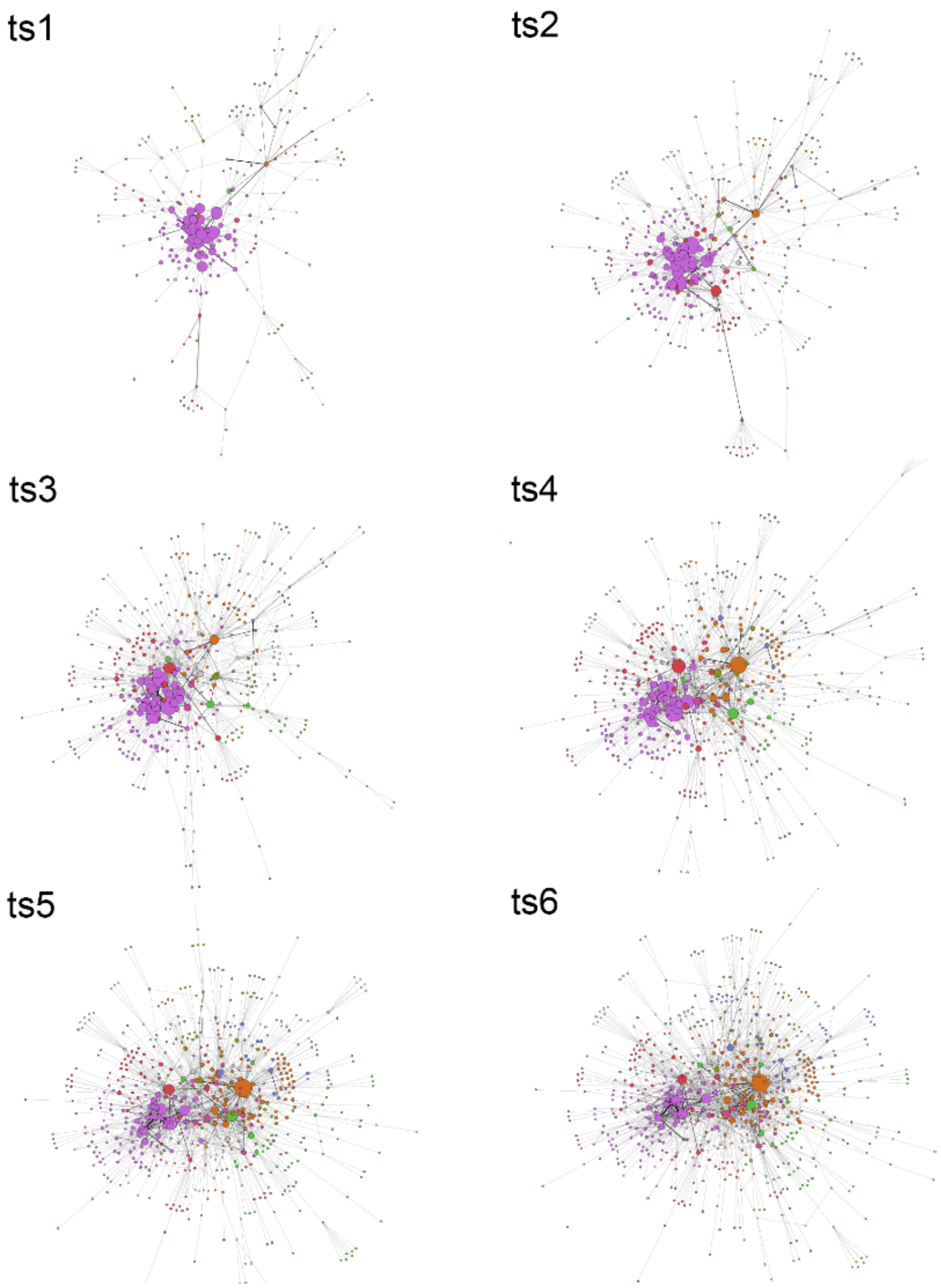

Figure 34 - Network evolution of the OpenAg Forum. Nodes sizes are defined based on individual Eigenvector values for each ts from ts1→ts6. Nodes colors are defined based on Modularity for ts10. (Source: Developed by the author)

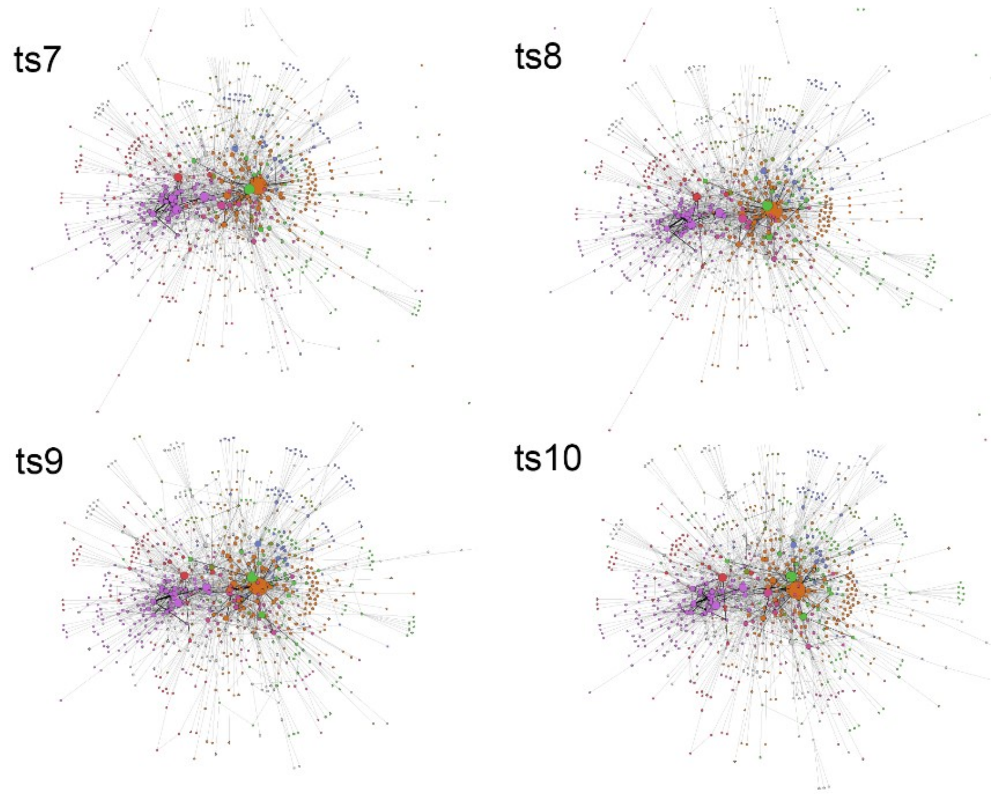

Figure 35 - Network evolution of the OpenAg Forum. Nodes sizes are defined based on individual Eigenvector values for each ts from ts7→ts10. Nodes colors are defined based on Modularity for ts10. (Source: Developed by the author)

It is also important to highlight that the optimum number of communities slightly decreased during the different periods we analyzed, ranging from 632 communities in ts=1 (modularity= 0.582) to 73 communities in ts=10 (modularity = 0.514). Although the modularity values decreased, we consider it to be insignificant given the variation in the optimum number of communities, indicating a tendency of the Forum community to be divided into clearer separated groups over time. Back to Figure 8, in ts=10, the colors indicate the modularity class of each node. Although the model resulted in 73 communities, only 7 of them accounted for a staggering 69,27% of the total of users, including those with higher EC values. These classes are represented in orange (22,13 percent of users), magenta (14,68 percent of users), light green (11,01 percent), red (10,09 percent), purple (8,49 percent), pink (7,11 percent) and dark green (5,85 percent).

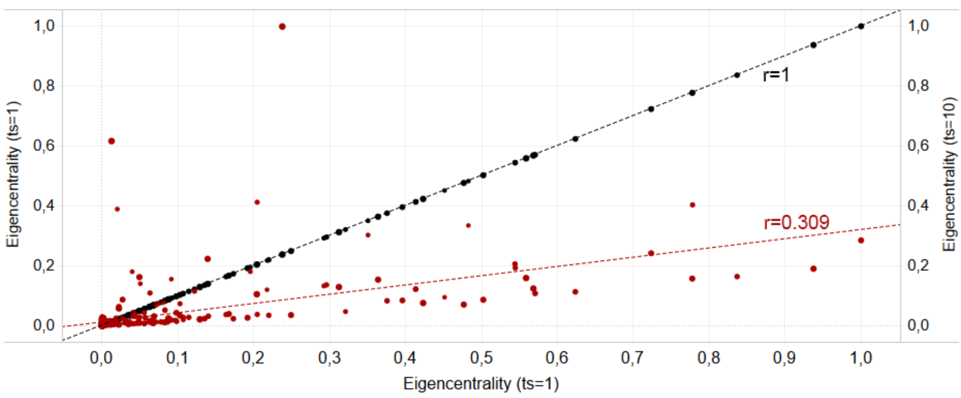

Figure 36 - Eigenvector variance between ts=1 (black) and ts=10(red). (Source: Developed by the author)

Finally, Figure 37 shows users' permanence based on their first activity in the Forum, e.g. signing up, and their last activity. The majority of users (34,36%) have interacted for only one day (0,00%) in the community, 36,90% interacted between 0,01% and 10,00% of the total number of possible days. On the other hand, the total of users with higher permanence values (above 70%) represent only 4,17% of the total. Amongst the 10 users with the highest EC values, 7 of them had a permanence value above 70%. It is important, however, to note that high permanence does not necessarily mean high consistency or constant posting.

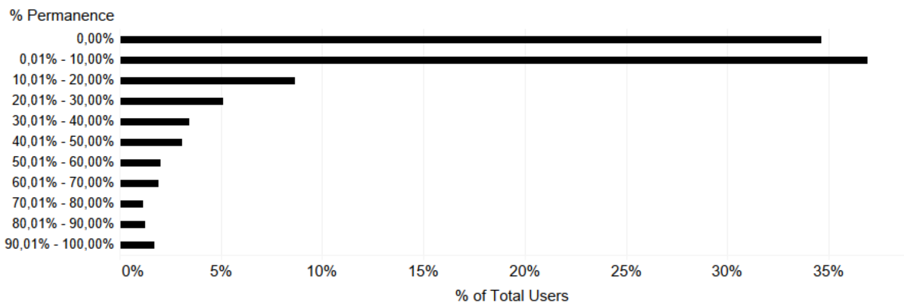

Figure 37 – Permanence (in percentage) of users in the community considering first and last activities (comments). 100 percent of permanence means that a user who participated in the community since his first comment until the September, 2019 (when we performed the data mining). (Source: Developed by the author)

RQ4c: Why do single-time users participate in the community and how do they affect the activity volume?

We considered single-time users those who participated in the community for a maximum of two times, either by starting a topic thread or by replying to someone else's post. As mentioned earlier, these users consist of 50,3% (471) of the total users. After the identification and categorization of key words, we identified the five main topics preferred by single-time users in the community. These are presented in Table 19 with some excerpts from messages retrieved.

First, the majority of users are involved in school or research projects, including educators and students from primary and secondary schools, undergraduate students and master students. In general, the comments are not always linked to a particular question about technicalities of the project but it is also a way for users to communicate their experience and express how the project outcomes benefits the learning environment. The Second and Third groups are related to users either building a PFC or interested in building one. The second group consists of users with a higher experience level and with more specific interests. For example, users with a background - or interest - in aeroponics and hydroponics might be interested in particular aspects of the project. Others would ask more specific questions and be left without any answer. As for the third group, it consists of users motivated in building a PFC but with very general questions regarding the costs involved, the types of plants it can grow, the materials and components it requires, the date of new versions' release (etc.). Fourth, users also showed particular interest in introducing themselves and the location they live. Some comments were also related to the availability of components at their location and possible alternatives for those which were not available. Others mentioned their interest in building PFCs or exchange information with other users at the same location. Finally, a less expressive group consists of users interested in presenting a business idea or contacting others for selling or buying products. Some users offered to buy the assembled PFCs or pay for assistance, while others tried to sell either components or the PFC.

Table 19 – Comments excerpts of single-time users based on the type of comment we mapped. Typos and grammatical errors were kept as in the original source (Source: OpenAg Forum) (Appendix D)

Type of comment	Comments excerpts of single-time users
School and Education	*"(...)This is connected to my research interests and I am definitely interested in getting involved. I am a Family & Consumer Sciences teacher at the middle school level, with an interdisciplinary background in tech, art/design, and Stem Integration. (...) This has great potential for a PBL initiative at my middle school. (...)"* *"(...) Our teacher showed us the Ted Talk that Caleb gave. We want to build one. We want to write a grant to get the money to build one and ask the High school Robotics team to help us with the coding. (...) Should we wait until kits are available? How much might the kits cost? How much of this would 8, 9 and 10 year olds be able to do?(...)"* *" I am middle school educator in the United States (Delaware) that is interested in bringing Food Computing to classrooms!,Some of my plants in my room are already being grown and shared. The personal food computer was inspiration, but too expensive"*
Builder (Advanced)	*"On running rosrun openag_brain main -f default, it shows an error that openag_lib.config not found"* *"Does anyone have experience substituting the chassis and frame material (Komatex as listed in the BOM) for delrin or another plastic? I would like to hear your assessment on how its affected the overall integrity of your pfc, as well as other notable observations.(...)"* *" I have some questions about using RBG LED strip as lightning for MVP build that I'm planning to do. (...) I'm planning to control the light using an arduino and adjust the intensity using PWM. Here comes my question: Does LED strips like this supply enough light? (If I e.g. used 5 m LED strip for an area of 0.1 m^2); Does the PWM harm the plants?; Any other concerns with this setup?"*
Builder (Beginning)	*"Hello Everyone,,I am new at this forum and I decided to build a PFC. I am waiting for version 2. Do you know when will it be published?,Thank you and keep working on agricultural revolution!"* *"(...)This is my first experience on building a Food Computer v3.0. Please anyone could share the following files in format .sldprt TBI, TBFB, TBFBH, TBLR, TBLRH, TBS and TBO.(...) The files above named are available in 3d file (stl file) but, as I said, this is my first experience with solidworks, I do no know how to import and edit in Solidworks so I can see the measure."* *"how much it costs to build a PFC?"* *"I am very eager to get started building a Food computer. However, I dont know if I should wait for V2.0 in september. How many hours do you think you spent to build it? If its not too long time, i may just built a V1.0, starting today…"*
Localities	*"(...) In Arg, some pieces are very expensive or almost impossible to get (… do not arrive), so maybe I should replace some products I am very happy building the MVP and I would like to being able to contribute to the advancement of development.(...)"* *"(...) Where in NZ are you guys? I am based in Wellington and very keen to get in to the food computer movement!"* *"(...)Hello, I'm located here in Colombia and I would like to start a PFC project as grower right now.!. Right now I'm looking for interested people near to my area of influence: Bogota, Colombia.(...)"*
Commercial	*"(...) I am very intrested in growing and not so intrested in tech or building. I guess there are a few people in this forum that feel the opposit, so why dont trade? Have you built the food computer and would like to sell it to me please send a e-mail to (...)"* *"(...) I live in korea and i will build PFC v2.0 soon. There are so many people who want to build PFC in korea but they are almost not a engineer so if i suceed in building , i want to sell it some people by crowd funding. Can it be a problem of copyright or license things?"* *"(...) We are interested in buidling a (several)PFC2 and would contribute all the necessary funds to make that happen. Do you have any interest in working with us? (...) We would supply the capital and your team would be the assembly/mfg. team."*

RQ4d: Can we identify important discussion topics based on Topic Modeling tools?

We performed the LDA analysis to highlight 8 topics, based on the average coherence scores illustrated in Table 18. The results in Table 20 show the 10 most salient words associated to each one of the topics and the key terms we defined for them. Topics 2, 3 and 4 are mostly related to aspects involving the environmental conditions for growing the plants. In general, Topic 2 seems more closely related to lighting influence in growth and taste, while Topic 3 is associated to the irrigation processes and nutrient feeding, e.g. adjusting the nozzles. Finally, Topic 4 seems to be related to more generic aspects of environment conditions, including temperature, water, humidity etc.

Topics 5, 6 and 7 focus on technical aspects of the system including the Hardware and Software. Topic 5 includes words such as light, BOM (Bill of Materials), cut, fan, led and box, which can be identified with Hardware Assembling and BOM. Both topics 6 and 7 are very similar and refer to the configuration of the system boards, e.g. Arduino and Raspberry Pi. Topic 6 is about running the different software codes, configuring the database and accessing data from sensors. It includes words such as data, file, database, code and software. As for Topic 7, it includes the words sensor, Arduino, code, connect and pin, being related to calibrating Arduino and accessing data from sensors.

Finally, Topics 1 and 8 are unrelated to technical aspects of the project but linked to educational initiatives and user participation in developing and testing design alternatives. Topic 1 includes the words "OpenAg, interested, project, great and think". In this sense, it seems more related to the comments of users interested in building PFCs and related comments. It also includes some contributions to the project. Finally, Topic 8 is defined by the words "food computer, student, group and project". It is strongly associated with School projects and the development of PFCs by high school and undergraduate students.

Table 20 – Latent topics and respective keywords resulted from the LDA analysis. The coherence score of the analysis is 0.5206.

Topics	Keywords										Definition
1	data	openag	interested	food	project	great	think	well	system	mvp	Similar initiaves and user participation in testing and
2	plant	recipe	seed	variety	think	light	may	taste	experiment	grow	Enviroment Control: Lighting influence in growing and taste
3	root	nozzle	system	chamber	mist	pump	reservoir	aeroponics	pressure	run	Enviroment Control: Irrigation and nutrient
4	plant	system	need	think	grow	growing	water	use	emperature	want	Environment control for growing: General aspects
5	light	water	bom	side	cut	two	fan	led	part	box	Hardware Assembling and BOM
6	data	file	running	need	couchdb	run	mvp	database	code	software	Software configurantion: database and sensors
7	sensor	arduino	code	using	connected	relay	connect	pin	working	image	Calibration of arduino and sensors
8	food_computer	pfc	project	build	building	working	student	help	thank	group	Educational Projects

Coherence Score: 0,520636421

The distribution of topics is presented in Table 20. The results indicate which topics tend to be more discussed in the community based on the average score they have for each comment. As for Figure 38, it presents the comments distribution based on their probability for each topic. Topic 6, related to Software configuration (database and sensors), is the most probable topic with an average probability value of 30,2% and 171 comments with a probability value above 90,0%. It is followed by the Topic 8, which has an average probability value of 28,0% and 65 comments above 90%. The following results are respectively Topic 1 (23,6% and 36 comments), Topic 4 (22,9% and 40 comments), Topic 5 (19,9% and 23 comments), Topic 7 (16,2% and 21 comments), Topic 3 (10,6% and 24 comments), and Topic 2 (10,2% and 4 comments).

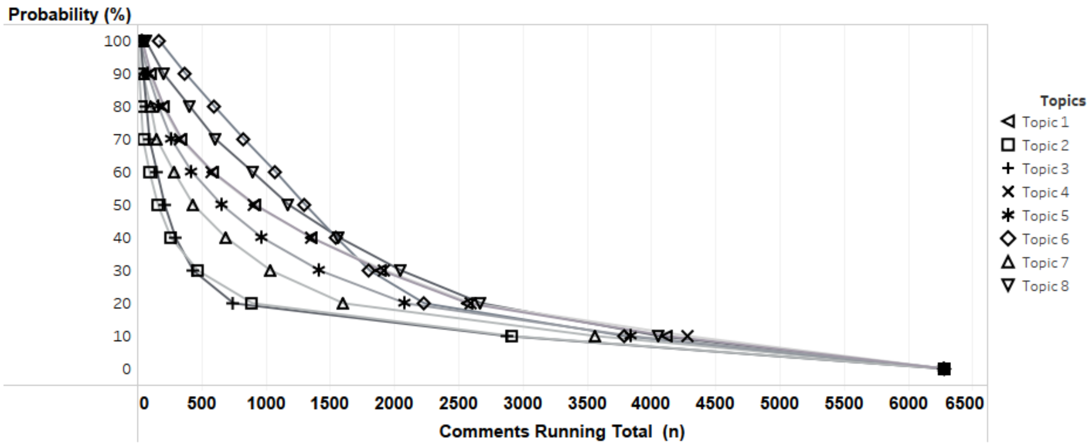

Figure 38 - Running total of comments based on their probability to belong to a specific topic. (Source: Developed by the author)

Discussion

We applied data mining techniques to explore whether the information collected would enable us to understand the structure of Open Design projects. For that purpose, we retrieved the metadata from the Open Agriculture Foundation project, available at their Community Forum Page and Github. Surveying the structure of OD projects and their corresponding communities is of much importance for our understanding of this emergent phenomenon and the possible factors that make a community effective.

Some observations and open questions

Regarding RQ4a, although there is a high heterogeneity of users with high activity in the Forum (70 users responsible for 50,12% of comments), Github commits are possibly limited to official OpenAg members (6 users responsible for 69,3% of the commits). These differences between the Forum and Github are noticed in the network analysis. Two different network structures for the Forum and the Github were identified. While the Forum presents a less centralized and more diverse network, in Github we note high centralization and lower diversity. In comparative terms, we can say that the Forum and Github networks are closely related to what Bonvoisin et al. (2018) classify as *"Closely connected decentral networks"* and *"Highly centralized projects"*, respectively.

The results for Github possible indicate a limitation of the decision-making process contributing to the debate regarding the extent of accessibility in OD projects, i.e. the degree to which any person can participate in the development process (BALKA; RAASCH; HERSTATT, 2010). At the same time, it is not possible to confirm whether the lack of accessibility is intentionally, i.e. limited by the OpenAg members, or reflects user's unfamiliarity to Github platform. Confirming this possibility would require further studies, e.g. interviewing members of the community. However, limitations for inexperienced users, in taking advantage of Github existing features, have been reported in studies as well (FELICIANO; STOREY; ZAGALSKY, 2016). As for the Forum, the most active users are represented by entrepreneurs, enthusiasts and OpenAg members. From our understanding, the Forum is a more intuitive platform for collaboration between users. It positively benefits replicability by enabling users to report issues and get feedback from the communities.

The role of entrepreneurs in sustaining OS communities is well reported in the literature, but mostly restricted to software development (YETIS-LARSSON; TEIGLAND; DOVBYSH, 2015). Although not directly involved in the decision-making process, these users are key actors for the community health. Our results also indicate a possible "mutualistic" relationship between entrepreneurs and the OD community. On the one hand, users take advantage of the open content developed to foster their product innovation processes and, on the other hand, the community benefits from the entrepreneur collaboration either by reporting/fixing errors, making suggestions or helping other users. Another example of the links between OS and entrepreneurs is the RepRap, an OS project for self-replicating 3d-printers. Started in 2005, the project originated the creation of companies for selling printer assembling kits and components, e.g. Bits from Bytes[12], and also 3d-printer suppliers based on the RepRap designs, e.g. MakerBot Industries.

Users with educational interests are also representative in the community. From our perspective, this is a valuable contribution of the OpenAg project. A considerable number of topics and comments, by students and instructors, were related to the development of similar school projects (Table 19), i.e. technology and food growing. We wonder whether these users continue collaborating with the community after completing their specific projects. However, the high number of single-time users with educational related inquiries indicates that this tends to be a low-permanence group.

As for RQ4b, the evolution of the Forum network indicates not only changes of users' importance and activity but also an increase in topics diversity. It started as a *"high centralized"* network, with OpenAg members associated to the most important nodes. This was an expected result if we consider that the Forum was created by the OpenAg members. An important remark is the fact that the initial structure of the Forum (2016) is similar to the structure we found in Github. However, the sequential network structure of the Forum becomes more diverse and less centralized, indicating that late external users can also become important actors of the community. We also observed a decrease in importance of OpenAg members, which, from the Open source perspective, is a desirable characteristic. It possibly indicates a stage where the community depends less on the original project's owner. However, we cannot conclude that this is the current stage of the community once the Github structure indicates that actual changes are still performed by the project owner. Given the recent nature of the project, continuous analysis of the community would enable us to verify, for instance, if the structure of the

[12] Bits From Bytes was a provider of affordable 3D Printers and 3D Printer kits. It was bought by 3D Systems Corporation in 2010.

Forum kept the decentralization/diversification process we have observed. It would be also possible to confirm, or not, the centralized nature of the Github community.

In RQ4c, we investigated the reasons that single-time users participated in the Forum community. Although the results do not allow us to draw precise conclusions about who these users are, some observations need to be highlighted. First, the wide variety of topics discussed by these users reflects the diversity we found in the community. These users commented upon topics related to commercial usage of the project and educational ideas, inquired about the PFC building process and searched for users from the same localities. Second, in OSS studies, authors identified that new users also joined the communities because they needed to solve a particular problem (BAGOZZI; DHOLAKIA, 2006; SHAH, 2005). This is also true for a number of users we identified. However, the analysis of the Forum showed that users may be motivated for different reasons, e.g. interested in agriculture techniques or in finding a new hobby. In fact, by tracing back the comments from the most active users (non OpenAg member), we managed to verify that they were particularly interested in plant growing systems prior the release of the project. Finally, the large number of single-time users (50,3%) indicates that the majority of potential collaborators stops contributing right after the first interactions with the community. As we also pointed out, over 50% of users have a low participation rate (less than 10%) considering the total time (from registration to the time data was acquired). We understand this to be a natural aspect of the OS ecosystem and, possibly, a positive one. It indicates some sort of enthusiasm or inspiration, even temporarily, at the same time it increases product replicability - by enabling users to ask questions about the building process and get support by the community.

The RQ4d considered the adoption of topic modeling tools to check whether it was possible to identify major topics discussed by the community. We evaluated the modeling output based on our familiarity to the forum posts, users and on the previous analysis we conducted. We note the existence of some cohesion between the topics generated from the LDA analysis and the community profile, i.e. the type of users, motivation and development process. Two of the topics refer to comments about education, user participation and similar ideas. These correlate to the users profiles we identified, especially students and teachers. The other six topics are linked to Hardware and software aspects of the project varying from more general ones to more specific ones. Another possible contribution of the LDA analysis is that the classification of issues into more detailed categories than those available in the Forum. Although posts are already divided in the Forum into 17 specific categories, many of them fit into different ones while others are posted in non-related categories. For example, posts related to temperature and humidity are observed in categories such as Hardware, Software, Electronics and Help. We wonder whether forums could benefit from applying topic modeling processes to organize the content created by users and help project curators to identify trend topics. Tagging systems based on LDA, for instance, have been proposed in other studies (KRESTEL; FANKHAUSER; NEJDL, 2009).

Limitations of the study

The limitations of this study are related both to the amount/quality of information accessible and to some of the results which are based on our own interpretation, such as the classifying of users' affiliation (education, work etc.). First, our analysis consisted of a single case which only allows us to draw some possible conclusions about the structure of OD projects. Therefore, future studies will need to explore a wider range of projects/datasets, which could confirm or reject our preliminary results. The data mining techniques we adopted, based on previous studies or proposed by us, could be valuable tools for such studies. Second, although our initial tests demonstrated the consistency of the approach, the methods adopted in the evaluation of user-to-user collaboration in the Forum platform are still limited. One possible alternative to investigate would be to consider only comments with direct mentions to other users. However, as we noticed, this would lead to a considerable decrease in the number of comments to be evaluated. Third, volume activity in both platforms showed a clear tendency to decrease over time. We wonder whether activity volume is influenced by events that are external to the collaboration platform and to the product development per se. We noted, for instance that some users joined the Forum community after watching a TED talk of the project creator. Fourth, users' affiliations were assigned based on their profile description and a keyword searching process. The obstacle of this approach is that it does not identify changes in users' interests, e.g. a student member who became an entrepreneur, demanding extra manual work for filtering the users. For larger datasets, automated classification processes would be needed to guarantee the analysis capacity. Finally, topic modelling has shown some potential for identifying latent topics in communities but its limitations need to be highlighted. These include (i) defining the optimum number of topics, which may vary significantly in short periods of time, (ii) identifying similar topics between comments in different languages and (iii) minimizing the possibility for overlapping topics.

Conclusion

In this study, we investigated the extent of knowledge created from mining data of OD project communication platforms, GitHub and Forum. We defined OpenAg as our research object and four RQs were developed. Based on the data we mined, we also drew some possible conclusions about this project structure which could be considered to other projects in general. The results indicated the high potential that data mining has for understanding OD projects dynamics and network.

Previous studies have proven the successful possibilities of data mining for investigations in the field of OS. With that in mind, we understand that our results and methodological approaches contribute to future researches on social structure of OSH and OD projects. They enabled us to identify, for instance, (i) some of the key users and how/whether they change overtime, (ii) their interests in participating in the community and (iii) the possible role of educational projects to foster collaboration in OD. From the practical perspective, it sheds some light in the understanding of the current status and limitations of remote collaborative design processes, especially related to users' participation, activity volume and content. Considering replicability one of the major aspects of OD, the optimization of such collaboration platforms could positively improve the way users with different expertise interact and make it easier for newcomers to participate and get help, e.g. addressing tags to post comments.

In future work, we therefore aim to confirm or reject our initial assumptions with a larger body of OD projects. In general, we consider that each one of our RQs could be further explored in future research. We find it particular interesting to continue the development of data mining techniques, to increase the number of platforms from which we can retrieve data directly and less noisy, i.e. without distortions.

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6 Discussion of Findings

This section is dedicated highlight the most important findings and draw the contributions of this research, based on the essays previously introduced. Implications for researches and professionals - in architecture and urban design - are also addressed in this section.

In this thesis, I investigated the concept of OD as an emergent phenomenon based on recent advances in ICTs. My aim was to identify its implications to the field of Architecture and Urban Design (A&UD). With support from literature and based on the findings from four studies, I argue that OD does hold promising implications to the field, although current hurdles exist. It is important to highlight that some inferences made in this research have the context of developing countries introduced in RQ1, RQ2 and RQ3 as background. It implies possible limitations regarding, for instance, access to technologies and skilled professionals. The discussion which follows therefore is not limited to, but strongly linked to this possible scenario.

Despite the rapidly growing interest of scholars in OD and OSH, the body of knowledge produced so far is still small if compared to researches in OSS, for example. Although some studies generally address the importance of skilled professionals (from any field) in the context of OD, it is not of my knowledge any attempt to deeper explore it from the professional perspective. Four research questions were then developed aiming at exploring the OD ecosystem, its claimed benefits, its limitations and its community structure (Table 21**)**. Research cases were selected based on some link either to Architecture or to Urban Design, e.g. furniture, urban gardening and residential automation.

Table 21 – Research Questions

	Research Questions
RQ1	How do the different aspects of openness affect artefact manufacturing?
RQ2	How does Open Design relate to sustainable development? What are the current limitations and possible pathways to overcome such limitations?
RQ3	What are the current challenges for replicability in OD and how to overcome them?
RQ4	What is the structure of an OD collaborative community? How and Why users collaborate?

To contextualize the research, I investigated the origins of OD – since the Free Software Movement - and pointed out that knowledge sharing with intents of increasing innovation, providing best-practice solutions and democratizing access to design, happened long before the rise of ICTs. Further, I adopted existing definitions in OD and structured it in terms of elements and principles. In RQ1 and RQ2, I included modularity as one of the principles of OD to assess projects manufacturability in DIY approaches and the easiness of design modification for different contexts. As for RQ3, I included modularity as one of the components of the design-for-DIY approach. In RQ3 I also suggested that replicability articulates both with transparency and accessibility, introduced by West and O'mahony (2008). For that reason, I propose a new framework for addressing the principles of OD, based on existing definitions and with some clearer differences between. A structured way to understand the relation between OD elements and principles is presented in

Table 22.

Table 22 – Elements and Principles of OD based on their importance to openness

Elements	Principles	Definition
Documentation	Accessibility	The extent to each any user/contributor can commit changes in documentation files once modifications are agreed by the community.
	Replicability/ Transparency	The quality/quantity of released documentation in order that allow an OD project to be executed/reproduced.
	Replicability	The information of alternative methods/materials to execute/reproduce a design object
Design Process	Accessibility	The extent to each any user/contributor can participate in the design development, including giving suggestions, reporting bugs and commenting on decision processes. Users can make decisions.
	Transparency	Full documentation of the design process in order to allow users/contributors to understand "what is happening and why" (West and O'mahony, 2008). Decisions are explained to users.
	Replicability	The willingness to adopt a design-for-DIY approach considering the availability of materials, components and "*vitamins*".
Sharing Freedoms	Replicability	The freedoms and restrictions applied to the designed object.

I also explored the links attributed by scholars between OD and (i) design democratization / citizen empowerment, (ii) distributed manufacturing and (iii) alternative innovations processes. These links were addressed in the RQs as illustrated in Figure 16 -Research Questions and links to OD. The results contributed to a better understanding of the OD phenomenon, enabling the validation/refutation of these claimed links. Based on current obstacles, some concluding considerations are drawn about the adoption of OD in A&UD.

As I showed in Section 3.2, OD in A&UD is not inexistent neither a novelty. Existing cases explicitly adopt the openness discourse to (i) develop micro-building units, e.g. Wikihouse, and (ii) architecture-related objects and components, e.g. furniture; and (iii) urban initiatives with the most different approaches which I defined as OUD. Others release self-designed objects in online repositories without any clear intention for collaborative development or to be acknowledged as an OD project – and it is not mandatory. However, the concept of OD seems to be still not clear for many. For example, the released documentation by the Chilean architectural firm Elemental[13] of some of its housing projects misses some crucial aspects of OD as the Bill of Materials (BOM), often considered when assessing openness of OD projects (BONVOISIN; MIES, 2018). This does not detract the importance of disclosing the design plans under a Creative Commons License. But it evidences that having a clear framework for OD, can help professionals (A&UD) to adopt it as an everyday practice and to get the benefits associated to it. The structure of elements and principles in

Table 22 is a viable starting point to be adopted by practitioners of OD in architecture and OUD. Besides that, the adoption of adequate sharing licenses is fundamental to preserver the original author's rights whilst guaranteeing the project openness. Therefore, a key practical contribution of this thesis is to introduce the concept

[13] Elemental released the plans, sections and elevations of four housing projects developed by the architectural firm. The documentation is shared both in .PDF and .DWG files.

of OD as a viable alternative to the professional (A&UD) practice with positive impacts to users/clients. Besides that, it also implies the possibility of professionals to collaborate in a non-structured way, i.e. without being part of a project team, and optimize the design process. This is a similar approach to the idea of open innovation (Section 2.1.2) when companies collaborate to each other for fostering innovation processes.

Is open really open? The findings suggest some discrepancies on the meaning of OD between companies, scholars and enthusiasts. This was expected as the concept itself is subject to different interpretations. Does limiting sharing rights, for instance, impedes a design to be open although it can be adopted for personal usage? By trying to answer that question, it seems plausible to confirm openness as a gradual quality of the OD object. It is therefore crucial to understand how the different characteristics of a project - regarding its documentation, design process and sharing rights – affect its openness. The development of standard guides for OSH, for instance, was initiated in 2019 by members of the OSH community, including practitioners and scholars (LAMM, 2019).

Further contributions are built based on cross-cutting findings from RQs (Table 21). Each contribution is discussed next. The first two contributions serve as a proposal to improve the design process of OD projects, especially in A&UD. Given the complexity of such project and with the aims of increasing the accessibility of the design processes I propose the adoption of a **metadesign** approach and **modularity** as a way to structure the design process. Complementary to the first two contributions, I will add the topic **education for OS** which encompasses the needed skills (i) for professionals to get involved in OD projects and (ii) for lay users who want to actively participate in OD processes. The reason for that is that one of the main hurdles for OS/OD development is the need for basic level for coding terminologies or digital design tools, for instance. As for the fourth contribution, it is the proposal of including **mobile factories as urban infrastructure**. As discussed in RQ1 and RQ3, a limiting factor to design democratization is that digital fabrication technologies are needed in a wide variety of OD/OSH projects. The idea of mobile factories had been discussed by (KOSTAKIS et al., 2015) and (FOX, 2014). I will add to that discussion the need of considering it as a basic service of urban infrastructure. Finally, the final contribution refers to the professional possibilities in the OD ecosystem. Throughout the discussion, I will also present possible paths for professionals (A&UD) to act within the OD ecosystem. These paths are built based on the knowledge built from these studies and existing businesses models discussed in the literature.

6.1 Metadesign

Concluding remark: Metadesign is a viable instrument to turn OD processes more accessible and OD objects more replicable.

In OS software development the technical barriers are often related to the need of coding expertise. As for the development of physical artefacts the technical barriers are of a greater range of possibilities, e.g. expertise in design digital tools and materials performance. In RQ1, I explored the manufacturability of open artefacts based on exiting documentation. Based on this process, I was able to identify existing limitations of some of the objects in terms of adaptation/modification so that they could be adjusted for local conditions. The exception was Bricksource, an open-source database of parametric brickwork. It's main advantage to the other projects explored is that it was designed to be modified and the parameters to do so were defined in the source documentation available. The fact that its documentation depended solely on proprietary software (*Rhino* and *Grasshopper)* was already discussed and I don't intend to advance in this matter. Said that, the important aspect to the discussion is that this parametric approach holds potential for improving accessibility and replicability of OD projects. In RQ3, I pointed out that it could benefit OD processes by enabling users to modify specific parameters without affecting the objects performance, e.g. associating a water tank size to its structural requirements. Parametric design is, however, the starting point of this discussion. Simply speaking, it refers to the parameters and rules which define an entity. A square, for example, can be described as having two basic rules and one parameter: *rules:* (i) it has four sides and (ii) its sides have equal lengths; and *parameter:* (i) the length of one side. However, if its position within a plane is important, the coordinates of its starting point, as a parameter, are also needed. Another valid point for parametrization is that it aims at the interaction between the user and the parameters. Although parametrization results from algorithmic design processes, I will adopt parametrization as I understand this interaction to be an important component for OD.

The bottom-line is that some level of **abstraction** is needed, if not required, to enable design appropriation in OD processes. However, the parametric approach is included within a bag of tools and strategies for design abstraction processes. In this level of abstraction, the role of the designer shifts from designing the object itself to designing the process of the design – from the object to its abstraction. This approach is defined as Metadesign. Commentators consider Metadesign to be the adequate approach for addressing collaborative and participatory design processes (FISCHER; SCHARFF, 2000), including in OD development (MENICHINELLI, 2015). It consists on the act of abstracting an entity to the point where its fundamental parameters are evidenced – from complexity to simplicity. It is important to note that this abstraction process may vary according to the premises and aims of the design itself. In practical terms its adoption in OD processes could enable lay users to actively participate on design modifications and improvements even if they are not familiar with some of the design tools and technical requirements. It also holds potential for increasing replicability by easing design adaptations. As for the professional, such as in A&UD, he acts at the abstraction level, providing the user with the means to design the possible object based on its attributes.

In Figure 39**,** I illustrate the OD structure when adopting the metadesign approach based on parametric design. (i) At the moment a goal (Ideal object) is defined, it is associated to a virtual object - with physical attributes. At this stage, a first moment of the OD can occur when users collaborate on the metadesign process for a particular decision environment. By decision environment I refer to the design platform (software) which enables parametric information. At this moment, a metaobject is defined (collaboratively or not) based on a set of attributes (constants and parameters) that. The metaobject is the first outcome of the OD process. The metaobject contains all the information needed to transform it into a "possible object". This process is oriented by the user who adjusts the parameters based on his own need. Multiple users (n) can therefore develop multiple possible objects (n) using a more user-friendly approach.

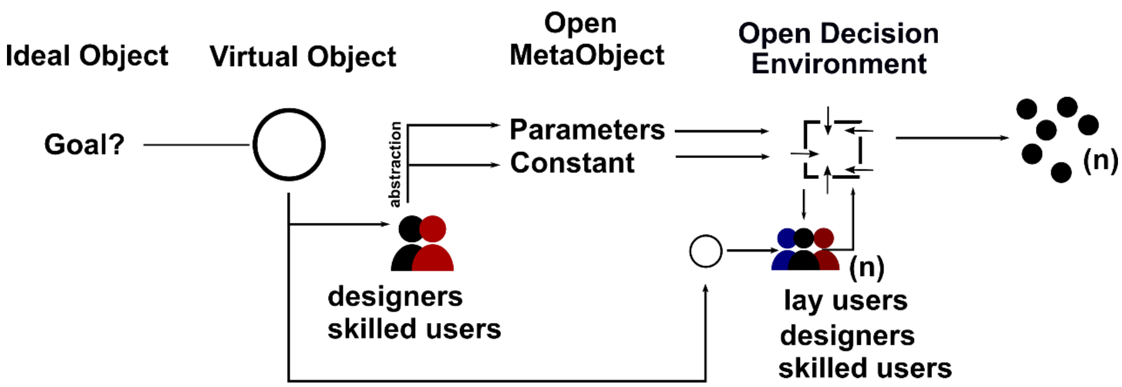

Figure 39 – A metadesign approach for OD processes. (Source: Developed by the author)

Besides parametric design, different tools can be adopted for conducting Metadesign. The patterns as a method, introduced in Section 2.1.3 when I comment about Christopher Alexander's patterns, is an alternative to such approach. Vassão (2008, p. 190) refers to patterns as the result of an abstracting process which converts an entity into a functional module. The functional module is constructed with two major principles: a recurrent problem and the core of the solution to it. It is however dynamic. The conversion of this functional module into an object – the ultimate goal of the design – may result in an infinite number of alternatives, based on the same principles. And why is it important for OD? I will argue that there are, at least, two reasons for that. First, it refers to the adoption of the patterns approach to facilitate collaboration practices in the absence of facilitators (VREEDE; KOLFSCHOTEN; BRIGGS, 2006), such as in OS development (LUKOSCH; SCHÜMMER, 2004). Second, it can be adopted for addressing recurrent design issues that are shared in unrelated OD projects. In fact, the Open Source Ecology (See RQ1) adopts a self-developed pattern language to make technology solutions more transparent and accessible to lay users (OPEN SOURCE ECOLOGY, 2017).

To conclude, metadesign explores all potential solutions but does not provide the output as a single viable alternative (DE MORAES, 2010). In this sense, it is plausible to assume that it responds to issues related to design replicability, identified in all studies (RQs 1, 2, 3 and 4): its appropriation for different contexts. In RQ4, for instance, it was possible to identify users with issues for adapting the designs to their local contexts. As for the context of UD, it can also serve as an instrument to articulate design processes in both small-scale interventions and large-scale ones, an issue identified by Manzini and Rizzo (2011) when investigating participatory processes. metadesign can also provide the means to increase user's accessibility – as defined in the principles of OD – by turning complex systems into abstract representations. I illustrated the possibility of two tools for metadesign processes, possibly the major ones: Parametric design and Patterns. Other possible examples of tools and methods that contribute to metadesign include conceptual mapping processes, systemic design and future scenarios envisioning.

6.2 Modular approach: elements and components

Concluding remark: Modular design reflects on OD replicability and accessibility by enhancing designs potential for modification and enabling users and professionals to focus on their topics of expertise.

In RQ1 and RQ2, I adopted modularity as one principle of OD, defining it as the possibility of a design to be separated into smaller components and elements, i.e. modules, to be designed separately with clearly defined interfaces. Further investigations however led me to consider it as one tool for replicability.

Balka (2011, p.73) states that there is a close link between complex objects and modularization. In OSS development, successful projects have shown that it is a common feature shared by them (MACCORMACK; RUSNAK; BALDWIN, 2011; NARDUZZO; ROSSI, 2003). Some of the findings from RQ1 and RQ2 also point to the direction that projects with certain degree of modularity had higher potential for being replicated than those with lower modularity. Although the OpenDesk furniture, for example, is considered a relatively simpler design when compared to others. Modularity is adopted for stacking or repetition, i.e. combining modules in different settings, but more important, some components of the furniture (joints, desk legs) also modular facilitating adjustments and adaptation. As for RQ3, I explored the OD potential for developing RWHs. By addressing it as a complex system, I explored its subsystems and corresponding components (filters, water tanks, gutters etc.). Although I highlighted important limitations, a modularity approach would enable each one of the components to be developed separately with compatible interfaces for assembling processes. Interface standardization is therefore encouraged, if not imperative, contributing to the generation of multiple possibilities of the same types of design objects with the same/similar ends.

Figure 40 illustrates the adoption of modular components in the development of an OD object. A virtual object is subdivided into functional modules which are independently developed but share compatible interfaces. Modules can be either classified as inbuilt, when they are essential to the development of a minimal functional object (MFO), or as addons, when they complement the functionalities of a MFO. Besides that, it is expected that modules are designed under an OD process. The adoption of outsource modules (or components) is due two major possibilities: the need for "vitamins", parts not suited for DIY production (as described in RQ3), or the adoption of OD modules from different projects. Outsource modules can be used either for the MFO and the fully function object.

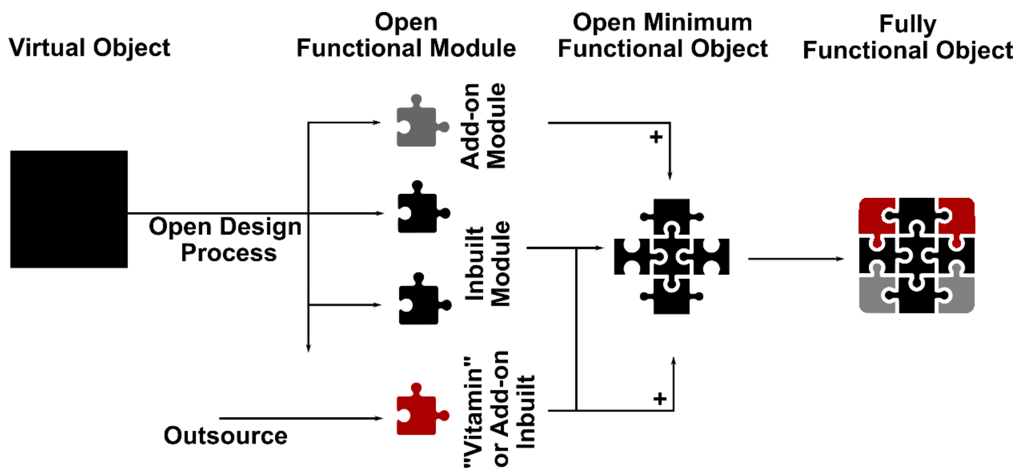

Figure 40 - Modular Approach to OD Objects. (Source: Developed by the author)

The benefits of modularity are associated to facilitated upgrade, adaptations, product assembly and disassembly, and customization (MONS et al., 2010; SONEGO; ECHEVESTE; GALVAN DEBARBA, 2018), aspects directly linked to replicability but also to bottom-up practices in A&UD. Finally, the in-depth analysis of the community in RQ4 enabled me to identify user's concerns regarding modularity with the purpose of constant upgrading. Users indicated their willingness to assemble the basic functions of the Personal Food Computer (PFC) and add other components over time. Such willingness resulted in the development of a Minimum Viable Product, as defined by the community. The development of a minimum functional modules, from a set of submodules, enables that approach. Focusing on modules also increases the quantity and quality of the model information, i.e. the needed information to produce a module and its specificities. In fact, as one of the findings from RQ2, I suggested that the environmental impacts could be also be assessed in OD project development. If those were embedded to the digital model, impact assessment could be significantly improved.

It is a valid strategy to address, for instance, common aspects associated to unsupervised self-building processes of dwellings, such as the need for building additions – popularly known as "*puxadinhos*" (MONTEIRO et al., 2009) - and other aesthetical/functional related ones, RWHs, openings etc. At the urban scale, I envision the possibility of applying it to poorer communities through the development of small interconnected OD modules for providing basic services of infrastructure, following the concept of Inverse Infrastructures (See 2.2.1), or acting in emergent situations. Over time, new modules could be implemented once new economic resources were made available.

As for skilled professionals (A&UD), the development of such components/modules, the management of such modular design activities, personalization-by-demand and supervision are considered possible alternatives for professional activities. These are also in line with existing businesses models identified in the literature, such as in the development of OSH for research equipment (PEARCE, 2017). In addition to that, modular components enhance the possibility for distributed manufacturing with possible implications in minimizing environmental, economic and social costs. However, distributed manufacturing will be discussed in Section 6.4.

6.3 Education for openness

Concluding remark: OD processes in A&UD demand participation of users and skilled professionals. As for professionals, a number of skills, outside their field of expertise, are important to enable them to take the most out of such processes. Furthermore, it triggers critical thinking while involving them in tackling contemporary issues.

It seems clear that a broader implementation of OD as an alternative to how we design and manufacture things implies new approaches to education, both for users and professionals. However, I will dedicate most of the discussion to the importance of new approaches for the education of professionals related to A&UD. Reasons are both related to the technical requirements for adopting OD projects and to the design process itself. The adoption of OSS have been suggested in computer science programs with benefits associated to the possibility of working in a "world-size laboratory" with support from experts and experience in collaborative development processes (HARA; KAY, 2003). In parallel to the benefits of adopting OSS in education, I argue that OD holds potential for educating professionals in new forms of collaboration based on the rise of new ICTs. As it was shown in RQ4, schools and teachers may adopt OD projects to develop themed school projects with students, such as indoor agriculture in the case of OpenAg.

Experience on collaboration platforms with version control is of high importance. In closed collaborative processes of A&UD, existing tools for management, visualization and modification are already adopted[14] and of valuable importance for remote collaboration. In OD however the process is slightly different. As collaborators are not defined, decision making processes tend to be less centralized. Users are free to report bugs, make commits, reply on other commits and fork the projects into new

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[14] BIM360 is a Construction Management software aimed at supporting teams' collaboration from design through construction.

projects. Version control guarantees backup, tracking modifications and exploring the project development. Unfamiliarity to such tools might move away potential collaborators (BONVOISIN et al., 2018). This was also commented in RQ4, when differences between participation in the OpenAg Forum and Github were compared. Github presented a lower participation rate than the Forum. Although it can also indicate some editing control by project's owners there is a high chance that lower participation in commits reflect that possibility. Conversance with tools currently used for OD could therefore be obtained by future professionals.

As some of the examples investigated in RQ1, RQ2 and RQ4 show, OD projects can share both hardware and software components and it is also a possibility for A&UD. The complexity and interdisciplinarity of some projects result in the need for a wide variety of skills, e.g. electronic components, CAD and programming. It is not expected one to have all the skills but familiarity is advantageous. More specifically, basic knowledge in software coding is therefore important for better understanding projects that share both hardware and software elements. For professionals (A&UD), even basic experience in coding can improve their autonomy in making suggestions and adapting codes, even if not related to the physical component per se. Van der Graaf & Veeckman (2014) illustrate the use of open public data by an initiative to the development of mobile applications supported by the city of Ghent, Belgium. One of the components of such initiative referred to the development of a toolkit, hosted by the municipality, which helped citizens to develop mobile applications without the need to code any single line. it is important however to highlight the limitations of such approach. Despite the benefits to the citizens the possibilities are limited to a set of pre-determined tools. On the other hand, the complete release of the source code, as it also happened, enabled users with coding skills to use it to meet personal goals. In RQ4, I identified a considerable number of entrepreneurs interested in adopting some features developed by the OpenAg community for creating new products. This is only possible if they have access to the complete source code and are capable of editing it to meet their demands. As for A&UD

professionals with coding skills are important to enable such initiatives by combining their field expertise (A&UD) to the development of such platforms and adopting it to the development of new projects. A possible implication in OD is the use of open data to develop interactive objects, for instance.

However, the reasons are also related to the design process itself. The line between software and the object is also very thin. Parametric design, such as in the façade from BrickSource (RQ1), is based on algorithmic thinking which adopts rules and parameters to provide a design output. Actually, existing software for CAD and BIM have interface for programming new functionalities aimed at optimizing recurrent tasks or managing design data/parameters, for instance. In parametric modeling, as well, different software[15] adopt visual programming in order to enable the user to develop and perform algorithmic design tasks. However, as mentioned earlier, this approach builds algorithmic thinking but is restricted by the pre-conceived toolboxes. This is important to include a wider range of users but more complex – and personal - issues will probably demand more familiarity with pure coding. It can help professionals therefore (i) to have full control of important parts of the design process, (ii) to improve the quality (information and performance) of OD object models, and (iii) support lay users.

Finally, involving students in OD projects contributes to triggering discussions about global related issues and enhances the capacity of students (future professionals) in design-for-appropriation, i.e. for being adapted to different contexts, and design-for-replicability processes (OSTUZZI et al., 2016). It is important that the learning environment enables the student to acquire a critical view about technology-based design processes and the adoption technology itself, such as digital manufacturing tools. Makerspaces and Fablabs, for example, have been considered as gamechangers for

[15] Examples of visual programming tools are Grasshopper and Dynamo - plugins for Rhino3D and Revit, respectively.

education at all levels by different authors (KOHTALA, 2016; NIAROS, 2016). The benefits of such technologies, however, are mostly dependent on social factors considered in the design process (DE CAMPOS; DIAS, 2018). Thus, educating for OD considers both the technological aspects of the design process, including remote collaboration and digital prototyping, and social aspects of it, including what are the purposes of the design and to whom is it being designed for.

6.4 Mobile factories as urban infrastructure

Concluding remark: Mobile factories are an alternative to the lack of access to manufacturing technologies and skilled professionals.

Finally, the last cross-cutting discussion refers to the manufacturing - and prototyping – of OD objects. The findings of all RQs point to the importance of digital fabrication facilities. In RQ1, I commented on the dependency on digital fabrication tools of all OD cases studies. An exception can be attributed to "Bricksource" whose also shared an alternative way to build the stencil parts (Figure 21). In RQ2 and RQ3, I commented on the limitations for replicability and accessibility in places which lack access to such technologies and skilled professionals to operate or instruct it. As mentioned in Section 3.1.2, distributed manufacturing has been studied by scholars and strongly associated to the maker community (KOHTALA, 2016) and to sustainable business practices (DAFERMOS, 2015).

Based on (i) the utopian idea of Gorz (2008), that digital fabrication serves as an alternative for poor communities to self-produce their own products, (ii) some of the findings from this research and (iii) existing literature, I argue that places for digital fabrication are now – or will be - part of contemporary urban infrastructure. Furthermore, the idea of mobile factories is an alternative for remote or communities with little investment capital. How could these mobile factories be implemented? Political initiative is seen as a key factor for fostering such production spaces. First by associating it to existing public services including schools, museums and libraries thus enabling educational approaches based on constructionism. Second by catalyzing OD-oriented companies which could provide the support for the needed manufacturing infrastructure (KOSTAKIS et al., 2015).

Mobile factories could be adopted, for instance, to address common problems communities may face, e.g. access to safe water. Considering that scenario for RWHs, which I explored in RQ3, each household has its particularities which affects the components of the systems, e.g. water demand and rooftop size. The adoption of a single solution therefore seems impracticable. A supportive argument for mobile factories is that digital fabrication capabilities, combined with modular and parametric OD projects, could enable *in locus* adaptation, adjustments and manufacturing of customized objects for specific functions. As for skilled professionals, they can provide local assistance to the use of digital fabrication tools, adapt/modify designs for local appropriation and repair faulty artefacts. Once the goals of the mobile factory are achieved, it can move to a different location. It is important to note that digital fabrication also holds potential for minimizing the need for large machinery – at least in some cases. Taking the Wikihouse as an example, its structural components are designed to fit a CNC-machine with a dimension of at least 1220mm x 2440mm, relatively small if considered that it can be used to build a whole structural system from it (WIKIHOUSEPROJECT, 2016). Sheathing panels are also designed to respect that dimensions.

Of course, it is not expected that distributed manufacturing to replace conventional large-scale manufacturing processes. It is however a possible alternative for improving the living environment (A&UD) through the use of OD objects designed for replicability, i.e. flexible and adaptable for local circumstances and based on digital fabrication. It is, at least when combined with OD, a tool for conviviality. As described by Ivan Illich (1975), it means the opposite of industrial activity, a way to provide users with

> *"(…) the freedom to make things among which they can live, or give shape to them according to their own tastes, and to put them to use in caring for and about others (…)" (ILLICH, 1973, p.11)*

The freedoms which define the FSM (Section 2.2) are not fully met if one has neither the tools nor the skills to actively participate and understand the design processes and to appropriate himself of technology. Metadesign and modular design are part of the design process with great potential for democratization design processes and make the lay user more active in the process. Mobile factories assisted by professionals, one the other hand, enable the transformation of the virtual object the real object, adjusted to the local context and to users' needs.

In this section, I proposed four requirements for a larger-scale adoption of OD by professionals in architecture and urban design. Based on the discussion, a final framework is presented considering the impact of three requirements: metadesign, modularity and mobile factories as urban infrastructure. Figure 41 illustrates a development scenario which includes the metadesign approach and the possibility of adopting modular design process. As mentioned earlier, the modularity of an object depends on the possibility of subdividing it into clear independent submodules with compatible interfaces. In the figure, I highlight the moments that open collaboration may occur (A1 and A2), professionals may assist other users (C1, C2 and C3) and the release the OD documentation (B1 and B2).

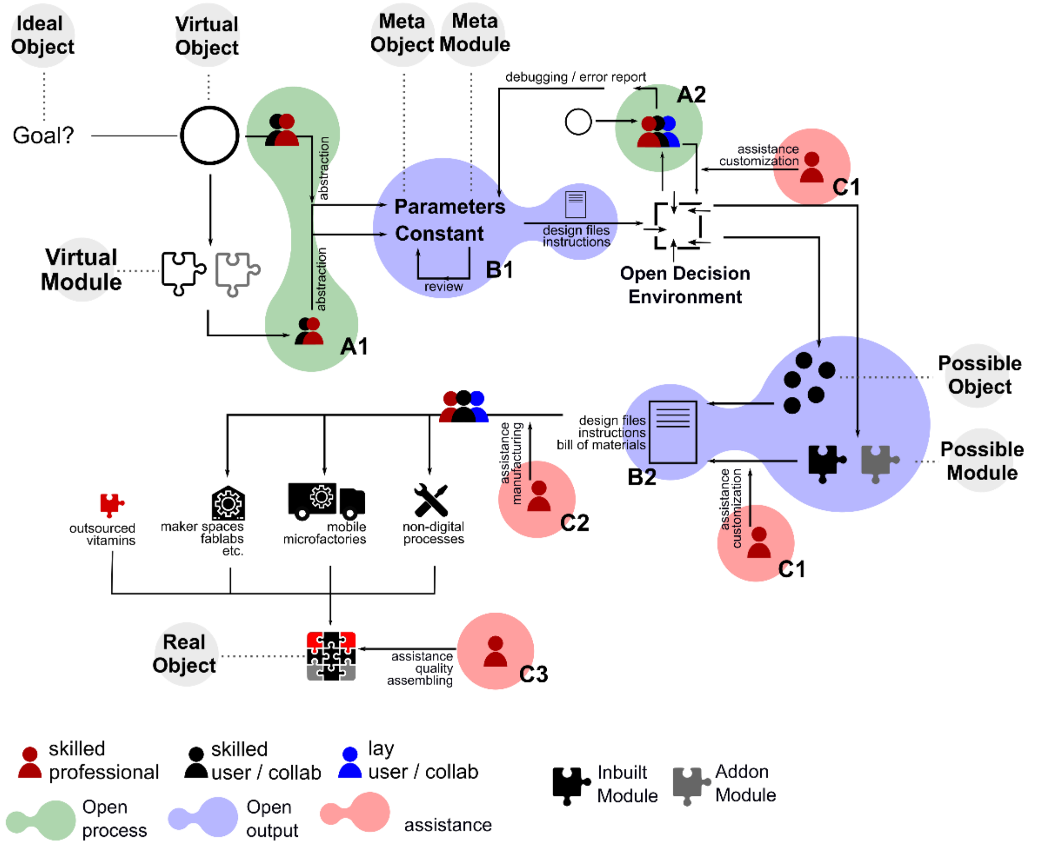

Figure 41 - A framework for OD processes based on metadesign and modular approaches. (Source: Developed by the author)

- At A1, skilled users (including professionals) collaborate in the development of the meta objects or modules (B1). The resulting output documentation is released (B1)
- B1 is adopted in a user-friendly platform (decision environment) to collaborate (A2) and develop *n* **possible** objects and modules (B2), and get assisted if wanted (C1). Debugging and error reports are used to feedback the metadesign.
- B2 is also released to the community and final users can adopt it to manufacture the object. Professionals can provide either design customization (C1) and manufacturing assistance (C2).
- The **real** object can be manufactured with the use of standard tools, makerspaces and fablabs, and mobile microfactories. Outsource modules/components can also be used to assemble the **real** object. Finally, the quality of the manufactured object can be assessed (C3) in cases where its safety and liability are important.

7 Conclusion

This research addressed Open Design (OD) as an emergent phenomenon with potential benefits to A&UD. Openness as a general concept, including Open Source Software and Open Source Hardware – for instance – has received considerable attention from scholars. Furthermore, open projects are constant surging in a wide range of different fields and some successful examples of commercial exploitation can be identified. As for A&UD, Do-it-yourself (DIY) Urbanism, DIY Urban Design and Open Source Urbanism are terms adopted by recent researches – since 2010 - to refer to urban processes which share similar principles with the open community. Researches on the implications of openness to design democratization, distributed manufacturing and sustainable development are also recent but growing in numbers. However, there is very limited research linking A&UD to the concept of openness. Consequently, the set of questions developed aimed at understanding OD, the differences between discourse and practice, current hurdles, the role of technology and the importance of OD communities. The research development inducted me to a new understanding about the topic from which some discussions could be drawn.

In practical terms, a major contribution to the field, is the structuring of OD elements and principles in a way that it is possible to professionals to be aware of the conditioning factors which affect openness. A clear understanding about what openness mean can help potential OD projects and practitioners to meet their ultimate goals by tackling the right elements. The discussions provided in this thesis can help with the emergence of new business activities by architects and urban designers in the light of OD. A sidekick contribution refers to guiding professionals about the importance of attributing sharing licenses to protect either the intellectual propriety – when desired – and the design freedoms.

Based on the findings, it is possible to argue for the viability of OD to change the way architects and urban designers work. Current hurdles however need to be tackled before it can be adopted by a larger audience, especially in poorer communities. From cross-cutting results of four RQs, four suggestions were made: (i) adoption of a metadesign approach, (ii) the adoption of modular designs, (iii) the education for openness and (iv) mobile microfactories as urban infrastructure. It is not expected that these suggestions will solve all current limitations OD. Instead, they offer a good starting point for future research work and tools development. How can we make collaborative tools to orient metadesign processes? How to include the lay user in the development of complex objects? Can OD help future professionals to develop new skills?

The interdisciplinarity of the topic also contributes to the rise of promising fields of research. They were introduced during the RQs and I will briefly comment on some of them. (1) Environmental benefits of OD are usually associated to the possibility of distributed manufacturing processes, and local materials. Sufficient quantitative information therefore is needed to strengthen this argument. Assessing OD projects in terms of environmental impacts, e.g. Life-cycle assessments, can be of much interest. (2) The liability and safety of OD projects is fundamental to guarantee a larger adoption. Although studies indicate the high rate of debugging in open projects, it is not certain that self-manufacturing processes are error-free. The development/adoption of OD metering tools and its assessment is suggested to guarantee more reliability in OD projects. (3) As for the analysis of communities, there is still a large uncertainty about users' behaviors, motivations and collaboration patterns. The adoption of data mining techniques proved to be an efficient way to start such studies. However, investigations are still in the early stages and further research with a larger number of cases might lead to additional understanding about how OD communities work.

To conclude, the development of further researches in OD is envisioned as collaborative development processes tend to continually grow. I also expect this research to contribute to the field of architecture and urban design by disclosing OD as a viable alternative to the professional practice and a pathway to address challenging issues faced by poorer communities.

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Appendices

Appendix A

Table 15

Aspects	System	References	Excerpt example
Taste / Odour	Collector, Storage, Supply	Amin and Han, 2011; Baguma et al., 2010; Campisano et al., 2017; Daoud et al., 2011; Kim et al., 2005; Kim et al, 2016; Mayo & Mashauri, 1991; Mwenge Kahinda et al., 2007; Nalwanga et al., 2016; Nguyen et al., 2013; Schets et al., 2010; Thomas, 1998	*"Materials used for construction such as cement and lime may impair the taste of water and scare away consumer."* (Mayo and Mashauri, 1991)
Component Materials	Collector, Storage, Supply	Arku, F. et al., 2015; Baguma and Loiskandl, 2010; Burt and Keiru, 2009; Campisano et al., 2017; Chang et al., 2004; Daoud et al., 2011; Ghimire and Johnston, 2015; Helmreich and Horn, 2009; Kim et al., 2005; Lo and Gould, 2015; Lye, 2009, 2003; Mayo and Mashauri, 1991; Morales-Pinzón et al., 2015b; Mwenge Kahinda et al., 2007; Nalwanga et al., 2016; Nguyen et al., 2013; Opare, 2012; Schets et al., 2010; Simmons et al., 2001; J. Song et al., 2009; Thomas, 1998; Tobin et al., 2013	*"(...) when subsidies in the form of RWH construction materials are provided, the chances of having a RWH system installed seem more."* (Baguma and Loiskandl, 2010)
Material Depositio	Collector, Supply	Arku et al., 2015; Baguma et al., 2010; Burt and Keiru, 2009; Campisano et al., 2017; Chang et al., 2004; Daoud et al., 2011; Han and Ki, 2010; Helmreich and Horn, 2009; Kim et al., 2005; Kus et al., 2010; Lee et al., 2016; Lye, 2009; Magyar et al., 2007; Mayo and Mashauri, 1991; Morales-Pinzón et al., 2015b; Mwenge Kahinda et al., 2007; Nalwanga et al., 2016; Nguyen et al., 2013; Opare, 2012; Schets et al., 2010; Simmons et al., 2001; Thomas, 1998; Tobin et al., 2013	*"(...)This suggests that after the contact with the roof, the rainwater was significantly contaminated by biopolymers and humic substances. This could be a result of atmospheric deposition."*(Kus et al., 2010)
Maintenance	Collector, Storage	Baguma et al., 2010; Campisano et al., 2017; Daoud et al., 2011; Gomes and Heller, 2016; Lo and Gould, 2015; Lye, 2009; Mayo and Mashauri, 1991; Mwenge Kahinda et al., 2007; Schets et al., 2010; Simmons et al., 2001; Thomas, 1998; Tobin et al., 2013	*"However, for other domestic purposes, (...) proper preventive and maintenance procedures may guard the microbiological quality and safe use of stored rainwater."* (Schets et al., 2010)
Positioning	Storage, Supply	Campisano et al., 2017; Han and Ki, 2010; Magyar et al., 2007; Mayo and Mashauri, 1991; Mwenge Kahinda et al., 2007; Nguyen et al., 2013	*"(...)And water outlets located at the bottom of the tank let sediments flow out with supplied water"* (Han and Ki, 2010)

Appendix B

Table 16 (Part A)

Replicability in OD			Statement	Classification Guidelines
Accessibility	1.a	What is the quantity and/or quality of information needed to replicate the hardware components?	Higher quantity/quality of information makes openness more difficult.	+2 Instructions and manuals +1 2D CAD drawings and plans -1 3D Models (low complexity/single components) -2 3D Models (high complexity/multiple components)
Transparency	1.b	How complex are the components in order to allow any user to participate in product development, including making suggestions and improvements?	Technical complexity demands expert knowledge to develop/modify designs. Suggestions are less dependent on knowledge but still affected by technical complexity	+2 Low complexity (No user experience) +1 Low complexity (User experience, e.g. design tools) -1 High Complexity (Technical Experience for structural modifications, e.g. storage dimensioning) -2 High Complexity (Technical Experience for specific modifications, e.g. filtering methods)
	1.c	What are the requirements for user participation in production development, including suggestions and improvements?	Higher requirements make the process less open. Ex. Computaional models are less open than Wiki/instructions development	+2 Textual suggestions are sufficient to improve designs +1 Textual and drawings are sufficient to improve designs -1 Knowledge in 2D CAD and 3D modelling tools -2 Knowledge in 2D/3D modelling and materials performance

Table 16 (Part B)

Replicability in DIY			Statement	Classification Guidelines
Materials	2.a	Are the components' materials widely available?	Availability of materials makes designs more likely to be replicated	+2 Non-processed materials without decreasing performance +1 Materials do not need special tools, e.g. Cement -1 Materials need specific tools, e.g. Aluminium sheets -2 Very specific materials, e.g. Biofilters
	2.b	Can the component be produced with a high variety of materials?	Material flexibility increases the chances of DIY approaches	+2 High variety of materials (+5 types) +1 Medium variety of materials (+3) -1 Low variety of materials (+2) -2 Low variety of materials (1)
	2.c	Can it be produced with standard tools?	Accessible and standard tools facilitate production processes	+2 Standard tools (mainly manual) +1 Standard tools (electric powered) -1 Non-standard tools (metal folding) -2 Very specific tools (3D-Printing, CNC-Milling)
Design Features	3.a	Does it enable flexible design? Can it be tailored according to the context?	Flexibility in design helps the design production in different contexts	+2 Standartization does not affect the system performance. Design appropriation in different locations need minor modifications +1 Standartization might decrease system performance. Complex modifications are needed to adapt designs -1 Standard components might not work in specific locations and adaptation requires structural modifications -2 Components' design cannot be adjusted
	3.b	Can it be designed for different depths of DIY?	Different locations have access to different tools/materials/skills. If designs are adjustable for different depths, chances of replication are higher	+2 Component does not need to be adjusted depending on the tools used +1 Component's design needs minor modifications depending on the tools used -1 Component's design needs major modifications depending on the tools used -2 It cannot be produced with different or manual tools

Appendix C

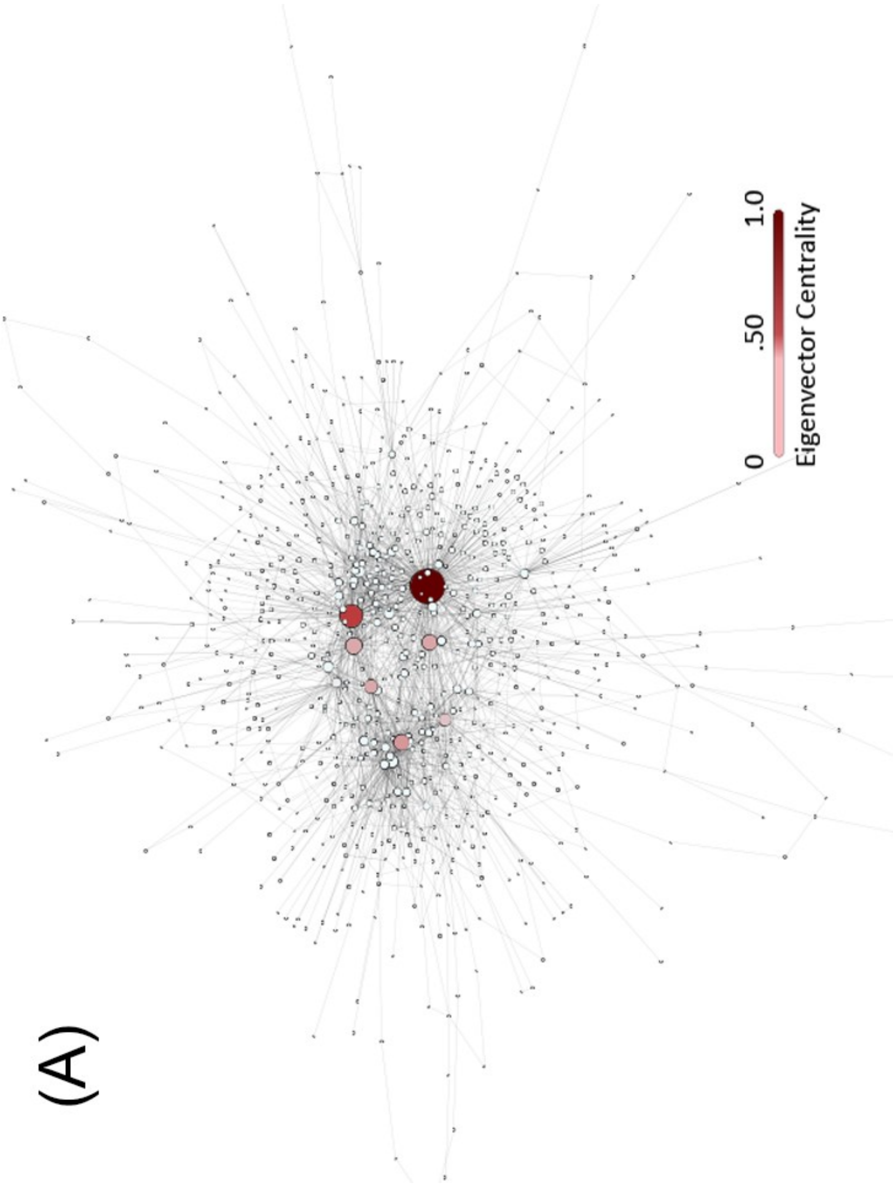
Python Script for mining data from OpenAg Forum – and other Discourse based forums. Available at: https://zenodo.org/record/3599786#.XiolICH-SUk

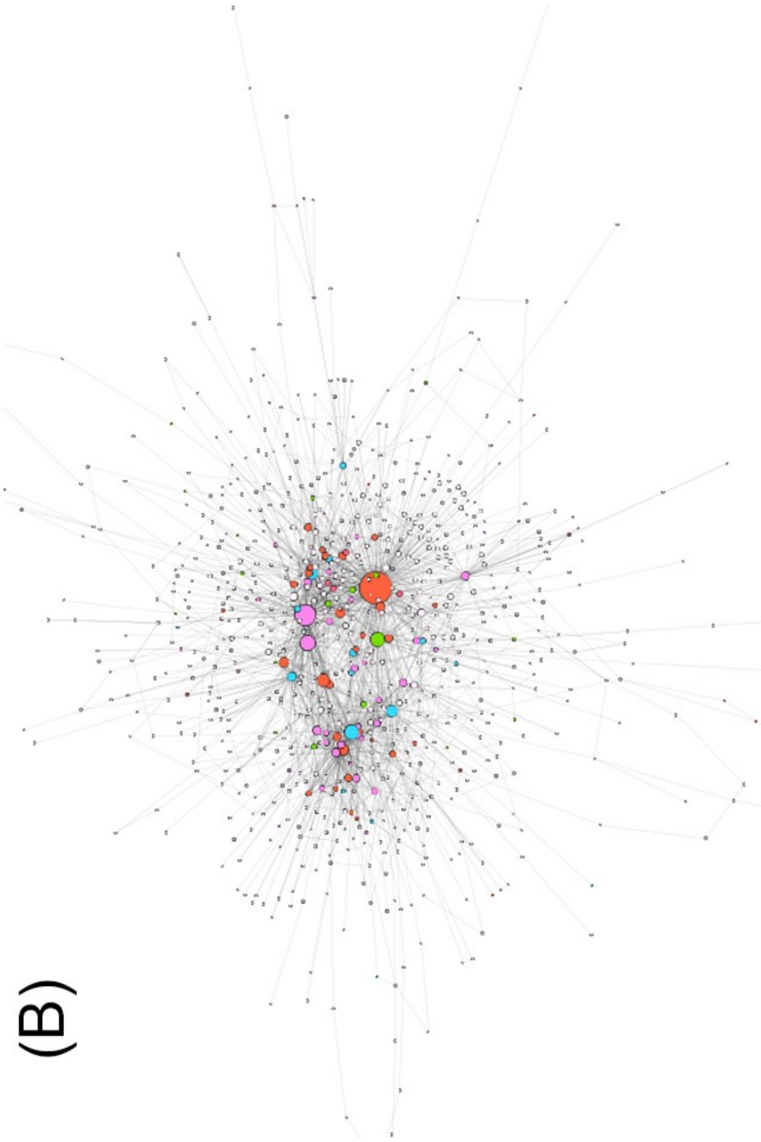
```
# Gets data from Discourse based Forum topics from a set of urls links which should be defined in url.csv (one link per line).
# Please, note that in order to make this spider to run, you will have to configure it manually to associate it to your scrapy project.
# You can also start a scrapy project, create a spider with the name of this spider and copy/paste this script to your spider script.
import scrapy
import csv
from scrapy import Request

class CommentSpider(scrapy.Spider):
    name = "topic_spider"

    #allowed_domains = ('https://forum.openag.media.mit.edu') ###This is not used in this script
    urls_complete = []
    file_urls = open("urls.csv", "r") # You will need a csv file with all the topic pages you want to scrap.
End of the file should have a ending statement "End of pages".
    for i in file_urls:
        u = i.split('\n')
        urls_complete.append(u[0])
        print('list of urls ' + i)

    for url in urls_complete:
        print('next urls are' + url)
    main_domain = 'https://forum.openag.media.mit.edu' #add your
    start_urls = [urls_complete.pop(0)] #Gets the first url of the file to be scrapped
    next_urls = urls_complete #Shows the remaining urls after removing the first url

    print('urls complete is' + str(urls_complete))
    print('start url is' + str(start_urls))
    #print('other url is'+str(other_urls))
    for url in urls_complete:
        print('next url is' + url)

    # Starts the requests for pages
    def start_request(self):

        start_urls = [self.urls_complete.pop(0)]
        print('start_request'+str(start_urls))
        yield Request(start_urls, self.parse)

    # Gets info of the responses including (author, text, mentions, time)
    def parse(self, response):

        for url in self.urls_complete:

            link_total = response.css('h1 a::attr(href)').extract_first(),
            file_type = ".csv",
            title_name = str(response.css('title::text').extract_first()) + ''.join(file_type),
            file_name = '-'.join(title_name).replace('"', '').replace(',', '-').replace('$', "_")
            urls_link = url
```

```
        topic_creator = response.css('span a span::text').extract_first()

    for comment in response.css('div.topic-body'):
        #author = comment.css('div span a span::text').extract_first(),
        full_text = ''.join(comment.css('div.post p::text').extract()),
        joined_text = [text.replace('\n', ' ') for text in full_text],
        #final_text = {}
        #title = str(response.css('title::text').extract_first())

        items = {
            'topic_creator': topic_creator,
            'user_comment': comment.css('div span a span::text').extract_first(),
            'author_id': comment.css('div article::attr(data-user-id'),
            'text': [text.replace('\n', ' ')for text in comment.css('div.post p::text').extract()],
            'mentions': comment.css('div.post p a::text').extract_first(),
            'time_1': comment.css('span meta::attr(content)').extract_first(),
            'time_2': comment.css('span time::attr(datetime)').extract_first(),
            'title': str(response.css('title::text').extract_first()),
        }

        yield items

    # Performs the scrapping process for next topic page
    first_page_url = response.css('h1 a::attr(href)').extract_first()
    next_page_url = response.css('link[rel=next]::attr(href)').extract_first()
    next_urls = self.next_urls

    if next_page_url is not None:
        next_page_url = response.urljoin(next_page_url)
        yield scrapy.Request(url=next_page_url, callback=self.parse)

    else:
        file_type = ".csv",
        title_name = str(response.css('title::text').extract_first()) + ''.join(file_type),
        file_name = '-'.join(title_name)
        first_page_url = response.urljoin(first_page_url)
        #task_urls = str(self.task_urls[0])
        #yield scrapy.Request(url=task_urls, callback=self.parse)
        print(str(next_urls))
        yield scrapy.Request(url=first_page_url, callback=self.parse_end)


# Gets info about the post
def parse_end(self, response):

    file_type = ".csv",
    title_name = str(response.css('title::text').extract_first())+''.join(file_type),

    results = {
        'Title': response.css('title::text').extract_first(),
        'Link': response.url,
        'Category': response.css('div div span::text').extract_first(),
        'Topic_Author': response.css('div span a span::text').extract_first(),
    }

    yield results
```

```
print('End of Topic Pages')

if self.next_urls:
    next_urls = [self.next_urls.pop(0)]
    for url in next_urls:
            print('next urls is ' + url)
            yield scrapy.Request(url=url, callback=self.parse)
else:
    print('end of scraping')
```

Appendix D





(B)

Appendix E

Table 19

Type	Comments excerpts of single-time users
School and Education	"(...)This is connected to my research interests and I am definitely interested in getting involved. I am a Family & Consumer Sciences teacher at the middle school level, with an interdisciplinary background in tech, art/design, and Stem Integration. (...) This has great potential for a PBL initiative at my middle school. (...)" "(...) Our teacher showed us the Ted Talk that Caleb gave. We want to build one. We want to write a grant to get the money to build one and ask the High school Robotics team to help us with the coding. (...) Should we wait until kits are available? How much might the kits cost? How much of this would 8, 9 and 10 year olds be able to do?(...)" " I am middle school educator in the United States (Delaware) that is interested in bringing Food Computing to classrooms!,Some of my plants in my room are already being grown and shared. The personal food computer was inspiration, but too expensive"
Builder (Advanced)	"On running rosrun openag_brain main -f default, it shows an error that openag_lib.config not found" "Does anyone have experience substituting the chassis and frame material (Komatex as listed in the BOM) for delrin or another plastic? I would like to hear your assessment on how its affected the overall integrity of your pfc, as well as other notable observations.(...)" " I have some questions about using RBG LED strip as lightning for MVP build that I'm planning to do. (...) I'm planning to control the light using an arduino and adjust the intensity using PWM. Here comes my question: Does LED strips like this supply enough light? (If I e.g. used 5 m LED strip for an area of 0.1 m^2); Does the PWM harm the plants?; Any other concerns with this setup?"

Builder (Beginning)	"Hello Everyone,,I am new at this forum and I decided to build a PFC. I am waiting for version 2. Do you know when will it be published? Thank you and keep working on agricultural revolution!" "(...)This is my first experience on building a Food Computer v3.0. Please anyone could share the following files in format .sldprt TBI, TBFB, TBFBH, TBLR, TBLRH, TBS and TBO.(...) The files above named are available in 3d file (stl file) but, as I said, this is my first experience with solidworks, I do not know how to import and edit in Solidworks so I can see the measure." "how much it costs to build a PFC?" "I am very eager to get started building a Food computer. However, I dont know if I should wait for V2.0 in september. How many hours do you think you spent to build it? If its not too long time, i may just built a V1.0, starting today…"
Localities	"(...) In Arg, some pieces are very expensive or almost impossible to get (… do not arrive), so maybe I should replace some products I am very happy building the MVP and I would like to being able to contribute to the advancement of development (...)" "(...) Where in NZ are you guys? I am based in Wellington and very keen to get in to the food computer movement!" "(...)Hello, I'm located here in Colombia and I would like to start a PFC project as grower right now.!. Right now I'm looking for interested people near to my area of influence: Bogota, Colombia.(...)"
Commercial	"(...) I am very intrested in growing and not so intrested in tech or building. I guess there are a few people in this forum that feel the opposit, so why dont trade? Have you built the food computer and would like to sell it to me please send a e-mail to (...)" "(...) I live in korea and i will build PFC v2.0 soon. There are so many people who want to build PFC in korea but they are almost not a engineer so if i suceed in building , i want to sell it some people by crowd funding. Can it be a problem of copyright or license things?" "(...) We are interested in buidling a (several)PFC2 and would contribute all the necessary funds to make that happen. Do you have any interest in working with us? (...) We would supply the capital and your team would be the assembly/mfg. team."