Free and Open Hardware:

A Critical and Thematic Analysis of Free and Open Hardware Communities RepRap and Arduino

Yilmaz Aliskan

PhD Media and Cultural Studies

University of Sussex

March 2021

I hereby declare that this thesis has not been and will not be, submitted in whole or part to another University for the award of any other degree.

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This thesis explores the issue of capitalist exploitation of digital media where free time and creativity are fundamental elements in the production of digital goods. The thesis focuses in particular on free open source hardware communities in which hackers give up a considerable amount of free or leisure time and creativity to produce open technology. Hardware hacking represents relatively new model designing and assembling of hardware based on commons-based peer production (CBPP). In this research, I examine how free time and creativity can be exploited in open source communities, with corporations benefiting from community wealth. I investigate how free or leisure time becomes a regime of "hyper-exploitation" from which capital is increasingly accumulated. It is hyper-exploitation precisely because, whereas workers receive wages in return to their labour, producers in CBPP are unpaid (Ritzer, 2014).

I focus on two Free Open Source Hardware (FOSHW) projects: RepRap and Arduino, as example cases in this thesis. Discussions on RepRap and Arduino mailing lists and the data from interviews are analysed. I explore how the free time and creativity of volunteers are exploited in FOSHW communities and how hackers react to capitalist exploitation. This thesis shows that hackers have differing aims and motivations in RepRap and Arduino communities. The discussions on the issue of open source, the issue of self-replicating, the issue of customisation, fun in the RepRap community and the issue of Arduino clones all provide a basis for analysing the logic of hyper-exploitation. Thjs in turn is based on the commercialisation of open hardware goods and the exploitation of voluntary labour which plays a key role in the production and distribution of software and design.

As a basis for further discussion, I introduce a set of key concepts that play an important role in the analysis of capitalist exploitation in Free Open Source Hardware (FOSHW) communities. These concepts include free time, creativity, capitalist exploitation, democracy, hacker, open source communities, collaboration, work, free labour and fun. I also discuss how the line between free time and work time is blurred

and the production of open source software and design has come to be seen as part of a free time activity. This thesis shows that free time and activity of volunteers in open source communities are exploited by technology companies and the term “fun” may disguise capitalist exploitation, in which the line between leisure time and work time is not clear. Creative activities taking place in free time create value that is appropriated by companies (see Kostakis and Bauwens, 2014). Even though hackers have fun when developing software and design, the efforts and creativity of hackers can be viewed as productive labour and therefore turn into capital in the market. The collaborative relationship between the firms and open source communities may enable capitalists to make a profit from peer production. I will discuss this issue in more detail in the thesis. The story of MakerBot in Chapter 5 and the issue of Arduino trademark in Chapter 6 provide us with important information enabling us to discuss in depth the hyper-exploitation of voluntary labour. I will scrutinise the concept of hyper-exploitation in Chapter 2.

Open source communities, on the one hand, allow humans to participate in the production of open technology. This can be also understood as the democratisation of production. Voluntary labour, on the other hand, may be appropriated by firms. In this thesis, I explore this contradiction in FOSHW communities.

In this research, I undertake interviews and collect data from the RepRap and Arduino mailing lists. I apply corpus text analysis and thematic analysis to the mailing lists and interview data. Two different empirical cases are used in the research. Firstly, Replicating Rapid Prototyper (RepRap) has been chosen in relation to the production and manufacturing of free-open-source 3D printers. RepRap is known as a self-replicating machine that produces most of its own components. Secondly, Arduino, itself a low-power open-source single-board computer has been selected as an empirical case.

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List of Abbreviations

ABS	Acrylonitrile Butadiene Styrene
BMCI	Banzi, Mellis, Cuartielles, Igoe
BNC	British National Corpus
CBPP	Commons-Based Peer Production
CC	Creative Commons
CEO	Chief Executive Officer
CII	Core Infrastructure Initiative
CTO	*Chief Technical Officer*
DIY	Do-It-Yourself
FOSHW	Free Open Source Hardware
FOSS	Free Open Source Software
FSF	Free Software Foundation
GPL	General Public License
HW	Hardware
IBM	The International Business Machines
ICT	Information and Communication Technology
IoT	Internet of Things
IPR	Intellectual Property Rights
LLC	Limited Liability Company
MIT	Massachusetts Institute of Technology
NAMM	National Association of Music Merchants
NC	Non-Commercial

ODF	Open Design Foundation
OHANDA	Open Hardware Design Alliance
OHL	Open Hardware License
OHSpec	Open Hardware Specification
OIN	Open Invention Network
OSHWA	Open Source Hardware Association
OSHW	Open Source Hardware
OSS	Open Source Software
PLA	Polylactic Acid
RepRap	Replication Rapid Prototyper
SRL	Società a Responsabilità Limitata
SW	Software
WIPO	World Intellectual Property Organisation
WWW	World Wide Web

Acknowledgements

As with any extended piece of writing, I have a long list of people to thank. Firstly, I owe thanks to my two supervisors Professor David M. Berry and Dr. Ben Roberts, who have been supportive, instructive, understanding and friendly during my PhD journey. Their advice, comments and criticisms have made the research much clearer and stronger.

I am also much obliged to Yasemin Ozgun, one of the signatories of the Academics for Peace petition, and John Hondros, both of whom were referees in my application for the PhD degree.

I would like to express my appreciation to all my interviewees. They made great contributions to my research with their experience, comments and views. I would also like to thank Wouter Spekkink and Eser Poyraz, who helped me in the cleaning process of the data and data analysis.

My parents, Kazim and Hunkar Aliskan, and my sisters, Nese Gul, Sengul and Derya, offered me considerable emotional support through the research process. They have always been supportive of me in my most difficult times.

A special thank you to my wife, Burcin Aliskan, for her unwavering love and support through our marriage. I could not have written this thesis without her, and I am truly thankful and lucky to have her by my side.

I also owe a great deal to my friends Umut Sahverdi, Umit Akyol, Erman Kar, Nermin Alkan Seval Erkul, Seyma Afacan and Murat Yildiz for discussions, comments and criticisms on my research.

Lastly, I would like to thank my grandfather, Hadi Aliskan, who passed away three years ago when I was in the UK, and my grandmother, Vahide Aliskan, who passed away three months ago. This thesis is dedicated to them.

Chapter1: Introduction:

This thesis explores the issue of capitalist exploitation in digital media where free time and creativity are important elements in the production of certain digital goods. My work focuses on free and open source hardware communities, in which hackers give up a considerable amount of free or leisure time and creativity to produce open technology. Hardware hacking represents relatively new model designing and assembling of hardware based on commons-based peer production (CBPP). I examine how free time and creativity can be exploited, indeed hyper exploited, in open source communities by corporations whose main aim is to accumulate capital.

The Free Open Source Hardware (FOSHW) projects: RepRap and Arduino are the example cases of this thesis. Discussions on the RepRap and Arduino mailing lists and the data from interviews are analysed. I explore how free time and creativity of volunteers might be exploited in FOSHW communities and how hackers can react to capitalist exploitation. This thesis shows that hackers have different aims and motivations in RepRap and Arduino communities. The discussions on the issue of open source, the issue of self-replicating, the issue of customisation, fun in the RepRap community and the issue of Arduino clones all provide a basis for analysing the logic of hyper-exploitation. Thjs in turn is based on the commercialisation of open hardware goods and the exploitation of voluntary labour which plays a key role in the production and distribution of software and design.

As a basis for further discussion, I introduce a set of key concepts that play an important role in the analysis of capitalist exploitation in FOSHW communities. These concepts include free time, creativity, capitalist exploitation, democracy, hacker, open source communities, collaboration, work, free labour and fun. I also discuss how the line between free time and work time is blurred and the production of open source software and design has come to be seen as part of a free time activity. This thesis shows that free time and activity of volunteers in open source communities are exploited by technology companies and the term “fun” may disguise capitalist exploitation, in which the line between leisure time and work time is not clear. Creative activities taking place in free time create value that is appropriated by companies (see Kostakis and Bauwens, 2014). Even though hackers have fun when developing software and design, the efforts and creativity of hackers represent productive labour and may be turned into profit in the market (see Berry 2008). The collaborative relationship between

the firms and open source communities sometimes enable capitalists to make a profit from peer production. I will discuss this issue in more detail later in the thesis. The story of MakerBot in Chapter 5 and the issue of Arduino trademark in Chapter 6 provide us with important information to discuss the "hyper-exploitation" of voluntary labour in more depth. Open source communities, on the one hand, enable people to participate in the production of open technology. Some call this the democratisation of production (Rifkin, 2014). Voluntary labour, on the other hand, can also be appropriated by tech firms, as I show later. In this thesis, I explore how these can be understood as the opportunities and challenges faced by FOSHW communities.

In this research, I undertake interviews and collect data from the RepRap and Arduino mailing lists. I apply corpus text analysis and thematic analysis to explain the mailing list and interview data. There are two different empirical cases. Firstly, Replicating Rapid Prototyper (RepRap); this has been selected for the purposes of understanding the production and manufacturing of free-open-source 3D printers. RepRap is also a self-replicating machine producing most of its own components. My other empirical case is that of Arduino, itself a low-power open-source single-board computer.

With this thesis, I make an original contribution to the relevant literature through my empirical work on interviews, analysing them within the particular field of FOSHW. I will use theoretical concepts to examine how the capitalist system exploits "productive fun labour" and creativity of contributors in FOSHW communities even while hardware hacking enables people to become contributors of open hardware designs.

Consequently, I have three research questions: 1) What can we learn from FOSHW communities in relation to issues of exploitation in commons-based peer production? 2) How do hardware hackers in FOSHW projects describe, understand and critique the organisational models of their communities? 3) What are the key ethical and ideological orientations of FOSHW communities?

These questions are important because former research has not sufficiently focused on FOSHW communities, therefore there is a gap in the literature. I will address this gap by looking at how voluntary labour within hardware hacking becomes a gradually more significant phenomenon in social production, and technology corporations increasingly develop a collaborative relationship with open source communities. I argue that the capitalist system establishes new regimes of capital accumulation based on the free time and creativity of volunteers, such as that found in

open source communities. Organisational models of open source communities are therefore a significant aspect of the literature that informs my research. There is a range of models, from bottom-up to top-down, and I draw on them to ascertain how the creativity of hackers in the community can be understood. The ideological dimension in communities is also important in understanding how certain political orientations become dominant. These orientations in turn trigger discussions, that give further insight into the exploitation of free time and creativity of volunteers.

In this chapter, I briefly examine capitalist exploitation, free time and creativity. Then I introduce the issue of peer production and FOSS communities. At the end of the chapter, I discuss how the internet enables users to empower their creativity and how Intellectual Property Rights (IPR) can become a bridge between creativity and capitalist exploitation. Empirical cases, RepRap and Arduino, are also introduced in this section. Lastly, the ideological distinctions within claims to being communitarian or libertarian are discussed. These differences will be used in the discussions of Chapter 5 and 6. Following Eagleton I understand "Ideology" to refer to "ideas and beliefs (whether true or false) which symbolize the conditions and life-experiences of a specific, socially significant group or class" (Eagleton, 1991, p.29). Now, I turn to the issue of capitalist exploitation, creativity, and free time.

The Issue of Capitalist Exploitation, Creativity, and Free Time.

Due to limitations on space in the thesis, I can only review a select range of literature on capitalist exploitation. I therefore concentrate on the discussions over capitalist exploitation, creativity, and free time and then move to discuss how creativity and free time might be exploited by the capitalist system in the twenty first century. However, I can give only brief summaries on types of exploitation in the capitalist system (but see Buzgalin and Kolganov, 2013, for more detailed discussion of this). On this point, I draw on the various categories of capitalist exploitation as outlined by Alexandr Buzgalin and Andrey Kolganov.

> 1) the "classical" system of hired labor and appropriation by capital of surplus value; 2) appropriation of monopoly (super) profits and financial profits; 3) partial social redistribution of a part of surplus value, and "diffusion" of capital; and 4) relations of exploitation that pertain to creative activity and appropriation of intellectual rent, which are specific to the current stage (Buzgalin and Kolganov, 2013, p.486).

This categorisation, made by Buzgalin and Kolganov, can be used to explore forms of capitalist exploitation. Even though each category of exploitation takes place in a certain historical moment, none completely vanishes. The classic definition of capitalism is a system of exploitation in which workers are paid in return for their labour-power. The accumulation of capital is based on surplus value of a commodity produced by waged workers (see Marx, 1990). The first, second and third forms mentioned in the above quotation might, at this point, be more appropriately understood through commodity fetishism[1] and exploitation of labour. The last one I will discuss in relation to the notions of autonomy, creativity, and free time.

Here, I believe that Marcuse is useful in thinking about these issues. He argues that "the technological processes which propel mechanization and standardization of production tend to eliminate individual autonomy" (Marcuse, 2001, p.50). Standardisation and mechanisation are not just related to the production of goods, they are also associated with the standardisation of individuals ("one-dimensional man") and society. He argues that humans become an object of technology if they lose their individual autonomy when operating technology (Marcuse, 2001). In other words, without individual autonomy (being a subject), humans cannot self-consciously shape but instead are shaped by technology.

The concept of "commodity fetishism" also represents a significant problem in the production of culture. Capitalism not only benefits from the commodity surplus value created by the producers, but also absorbs their creativity by commodifying cultural goods through standardisation and mass production. Horkheimer and Adorno explain that,

> ...with the ending of free exchange, commodities have forfeited all economic qualities except their fetish character, this character has spread like a cataract across the life of society in all its aspects. The countless agencies of mass production and its culture impress standardized behaviour on the individual as the only natural, decent, and rational one. Individuals define themselves now only as things, statistical elements, successes or failures (2002, p.21).

[1] Commodity fetishism is a valuable concept in the analysis of capitalist exploitation. A fetish refers to an object believed to have magical properties (Hesmondhalgh and Baker, 2011). Commodity fetishism means that commodity production "conceals the social character of private labour and the social relations between the individual workers, by making those relations appear as relations between material objects, instead of revealing them plainly" (Marx, 1990, p.168-169). Commodity fetishism mystifies social relations (Roberts and Cremin, 2019). The roles of social relations are ignored in production. Whether people are aware of what they do, they mostly do it (see Fuchs, 2015).

Culture is now an industry because culture- indeed mass culture- is standardised and commodified. The main character of the culture industry is sameness. Creativity is not part of the consumption processes in the cultural industry.[2] Capitalism limits the part humans play in the role of active subject in the culture industry, turning everyone into consumers. Repetition is the element of mass culture. Individuals have limited autonomy to make a difference, and they are replaceable as individuals (Hoikheimer and Adorno, 2002).

Capitalist exploitation is not just about the exploitation of workers' labour, but also the exploitation of creativity (Buzgalin and Kolganov, 2013). Hesmondhalgh and Baker (2011, p.383) argue that "people and societies become estranged from the products of their labor, from the process of production, and from their own nature as humans". Creativity can be possible with a co-creative endeavour, but the culture industry does not allow the masses to play an active role in cultural production (see Hoikheimer and Adorno, 2002). The culture industry makes people passive actors in the production process. As this industry is based on the standardisation and mass production of culture, creativity bends to the profit-seeking demands of contemporary capitalism.

The resources of creativity comprise several elements such as information and the results of social, artistic, educational, technical and scientific activity. Buzgalin and Kolganov (2013) assert that creative labour involves unalienated cooperation between people in limitless time and social space.[3] There can be genuine co-creativity, resulting from a dynamic communication process with all creators having a broad range of experience and skills, from professionals and the highly skilled to amateurs.

Buzgalin and Kolganov (Ibid) also state that creativity does not create surplus value, but instead universal social wealth, since creativity becomes the output of the collective activity of co-creators based on unalienated interaction, instead of it being based on the abstract labour of workers. They assert that some capitalists no longer exploit the labour power of workers, but instead the creative potential of a person

[2] Creativity has a strong relationship with hacking activities where hackers create something challenging and interesting. Creative activities are collective activities in open source communities with dynamic interaction. In this thesis, I define that creativity is a type of labour with an emphasis on the expressive, aesthetic and digital symbol and goods making. Autonomy and individual responsibility are vital elements of creativity (see (Hesmondhalgh and Baker, 2011).

[3] Marxist theory claims that labour becomes an alienated form of work that causes social inequalities (Fuchs and Sevignani, 2013). Buzgalin and Kolganov' claim, which include the concept of labour and unalienated cooperation, is interesting in this regard.

because time spent in creativity is free time,[4] not work time.[5] The claim of Buzgalin and Kolganov is quite controversial as I think the line between work time and free time is no longer completely determinate, but increasingly blurred (Hesmondhalgh, 2010; Bull, 2000). The claim that creativity is a product of free time can reduce creativity to certain leisure activities. There are many making money (a living) from their creative labour (Raymond, 2001). Hackers, for example, claim to have "fun" and become more productive when making a product from their voluntary labour. The product of a creator can be used as an instrument of exchange to make a living.

As Horkheimer and Adorno claim that "everything has value only in so far as it can be exchanged, not in so far as it is something in itself" (Horkheimer and Adorno, 2002, p.66), it might be of use to explain the function of the commodity, which is the cell of capitalist production (Marx,1990). The commodity, in terms of its functions, is made up of two values: "use value" and "exchange value." According to Karl Marx, (Ibid, p.125) "the usefulness of a thing makes it a use value", "use-values are only realized in use or in consumption" while exchange value "… appears first of all as the quantitative relation, the proportion, in which use-values of one kind exchange for use values of another kind. This relation changes constantly with time and place" (Ibid, p.126). The things used by people to meet their needs have use value, but the cost of things on the market is their exchange value. In this sense, the product of creativity also creates surplus value. If their creations have exchange value in the market, even if the creators are not hired workers or do not work for a company, said creativity absolutely creates surplus value, which serves the accumulation of capital.

Surplus value fundamentally derives from the surplus labour of workers (see Roberts and Cremin, 2019; Marx, 1990). It is, therefore, a significant element in a particular critique of capitalist exploitation that paves the way for social injustice. Only productive labour creates surplus value. The concept of productive labour can play a key role in this discussion to understand how capitalism exploits creative activity and

[4] Free time refers to the time spent on self-realisation and self-development. Michael Bull claims that free time means time away from work (Bull, 2000, p.161). In this thesis, I have borrowed the concept of free labour from Terranova (2004, p.74) "voluntarily given and unwaged, enjoyed and exploited", and free labour consists of collaboration practices that emerged on mailing lists, wikis and websites. Of course, free labour is not limited to only these activities.

[5] Work in this thesis refers to a set of activities in which people benefit from machines and tools to change nature, culture and society. Products and services are created to meet peoples' needs. Labour becomes an alienated form of work, in which producers do not own production tools (Fuchs and Sevignani, 2013).

free time. Similarly, Christian Fuchs (2015, p.129-138) points out that productive labour has three definitions: "(1) work that produces use value, (2) labour that produces capital and surplus value for accumulation, (3) labour of the combined and collective worker: work that contributes to the production of surplus value and capital".

Productive labour also creates use value, not just surplus value, but Fuchs' second and third definitions are more useful for thinking about capitalist exploitation under computation. The second one is more appropriate to hired labourers working for a company or a factory. The third seems much more relevant to the discussion of collective production, in which creativity has an important role to play in the production of surplus value, but the line between work time and free time is not strictly determined. Hackers are mostly not classical waged workers, because the creative labour given of producers cannot be measured by work time. Creative activity is exploited in contemporary capitalist society (see Aparici et al., 2019). Creativity can become an important aspect of social production. It is time to define the term social production emerging in community-based or collective production, as defined by Michael Hardt and Antonio Negri.

Social production means that production becomes increasingly social in a double sense. Humans, on the one side, participate ever more socially in the production process through networks of cooperation and interaction; on the other side, the outcomes of production comprise not only commodities but social relations, and eventually society itself (Hardt and Negri, 2017, p.xv). The production process is no longer limited to a factory or a firm, rather it extends to society. This does not mean that there is not another production model besides social production. Hardt and Negri (2017) claim that social production is a more democratic model of production,[6] in which people can be easily part of the production of knowledge and cultural goods. However, it is important to note that commodity fetishism could be a significant fetter for social production, if the role of social relations in the production process is ignored. Social production is a useful concept in the understanding of the production model based on online or offline networking platforms, where volunteers give up free labour. What is free labour then?

[6] Democracy, in the thesis, refers to "producing common good for all" (Lund and Venalainen, 2016, p.82). Participatory democracy also means the ability to participate in the production process (P2P Foundation, 2009). Peter Drahos and John Braithwaite (2002, p.4) claim that "the exchange, circulation and communication of information among people is fundamental to the way a democracy works". In this sense, peer production can be defined as a democratic production model

Free labour is used a concept that examines capitalist exploitation taking place in creative activity and in a commons, where humans make a contribution to collective production. Tiziana Terranova (2004, p.74) asserts that free labour is "simultaneously voluntarily given and unwaged, enjoyed and exploited [….] free labour on the Net includes the activity of building web sites, modifying software packages, reading and participating in mailing lists and building virtual spaces". Free labour here consists of activities in which people are not directly paid for their contributions to digital space.

Hardt and Negri (2001) use the notion of immaterial labour leading to the production of immaterial goods such as communication, knowledge, a cultural good, a service and so on. Immaterial labour, therefore, can also be the labour performed on a digital platform. Immaterial labour is a broader term used for the post-industrial era, ranging from the service economy to the digital economy. The term digital labour is more appropriate than immaterial labour in this research as the subject of this thesis is FOSHW and CBPP, which constitute a production model based on digital platforms. Furthermore, the production and distribution of hardware designs are based on online communities. Peter Fleming (2013, p.124) uses the concept of free work, which refers to "corporate activity that seeks to exploit the nonmetric qualities of social labor underlying so many moments of innovation, learning, and creativity in the workplace".

The activities not paid for on the internet can also be defined as unpaid labour, digital labour or play labour/playbour (Fuchs, 2014a; Kücklich, 2005). Christian Fuchs argues that unpaid labour is mostly used for economic surveillance on corporate social media. Fuchs calls creators of unpaid labour on social media "prosumers", who are at the same time both producers and consumers in the production process. Social media corporations provide these prosumers with a social network platform to generate data about their gender, sexual orientations, consumer habits, political views, hobbies, education levels, skills, national identities and so on. The personal data created by prosumers is stored, merged and analysed by these corporations and sold on to advertising companies, which in turn produce personalised ads for prosumers on the internet. Thus, with the help of social media corporations and willing prosumers, advertising companies know personal and even intimate details of said prosumers, can address these with personalised advertisement and thus commodify them for their own economic interests (see Fuchs, 2014b; 2015).

User generated content is another useful concept that refers to the production of users' material on Wikipedia, blogs, various types of interactive games, social network

platforms and so on (Hesmondhalgh, 2010). User generated content constitutes mostly unpaid work. Social media corporations have built their network platforms on user generated content, while users mostly do not pay service fees to the corporations. Communication and interactions between users energise social network platforms and increase the data created by users. The work of users grows the number of new users visiting the platform, and as the attention created by content increases traction, the corporations ultimately benefit.

It is claimed that social network corporations, in particular Facebook, YouTube and Twitter, may be considered democratic platforms where people can participate in the production of content (Shirky, 2008). On the other hand, an interactive communication process on social network platforms has to be treated with caution, since interactive communication itself is not sufficient for the democratisation of production. Fuchs (2015) asserts that participatory culture and a participatory economy are used as ideological concepts that hide the interest of social network corporations.[7] Power structures on social network platforms do not provide users to create a democratic space where users can participate in the decision-making process about the platforms.

Arwid Lund and Juhana Venalainen (2016) state that Wikipedia, at this point, does not make profits from the commodification of personal data of users. Wikipedia is a non-profit foundation, mostly based on donations made by users and supporters around the world. The foundation covers its expenses, such as network infrastructure and employee wages, with donations. However, most of the platforms based on user generated content are of commercial social network corporations that collect users' private data to post commercials in order to make a profit (see Fuchs, 2014a).

Play labour or playbour is another important notion that is used in the literature to define unpaid work in the digital game industry. Players are not mere consumers of the game industry; they also create their own games using the tools provided by the games manufacturers. The main issue here is that activities taken place in leisure time are commodified by the game industry. The industry does not simply sell entertainment products, but also exploits the activities of leisure time (Kücklich, 2005).

Julian Kücklich (2005) diffentiates "productive leisure", which includes woodworking, knitting, fishing and so on, from "unproductive leisure" which contains

[7] Ideology means "mysterious character of the commodity-form" (Marx, 1990, p.164). Here, ideology refers to the mysterious character of the activities of social network platforms.

watching TV, trekking, listening to music and so on. The term productive leisure is an important contribution to the discussion of free and leisure time. Creative activity taking place in leisure time can be exploited by the capitalist system. Creative activity in this instance is mostly based on productive leisure time, in which creators produce something new rather than monotonously consuming the same leisure activity. This definition is quite similar to the term hacking, which implies doing something interesting and challenging while having fun (Torvalds, 2001, p.xv). However, I would argue that playbour is not a suitable term in defining the activity of hacking, since the main motivation of players is to have fun when playing a game, but the main motivation of hackers is to solve a problem in a clever way.[8] It is "the mental gymnastics involved in trying to explain the universe" (Ibid). The term fun means "doing something we do well for the sheer pleasure of doing it" (Graeber, 2014). Linus Torvalds (Ibid) says that fun is more than just playing games. Playbour seems more appropriate for the game industry, rather than hacking.

Even though Julian Kücklich explains the activities of open source communities with the concept of playbour,[9] I argue that playbour is not a sufficient term to define the creative activity in peer production. If the notion of play was used as a competition between creators to solve a problem or produce a new thing, the term playbour would be meaningful for the creative activity of hackers, but it is a confusing notion that cannot differ productive leisure from unproductive leisure. In this sense, playbour is insufficient in explaining the activity of free open source communities. Therefore, I argue that there is an important gap in the literature in the defining of productive leisure time in open source communities. I introduce the term "productive fun labour" to define volunteer activities in open source communities. By fun, I mean voluntary production in FOSHW. The term fun refers to "productive leisure" time including hacking. It is different from "unproductive leisure" such as playing a video game or listening to music. Many volunteers participate in the production of open hardware and having fun

[8] The hacker is a concept used for a person who is "an enthusiast, an artist, a tinkerer, a problem solver, an expert" (Raymond, 2001, p.xii). I use Eric Raymond's definition of the hacker.

[9] Open source communities contain programmers and non-programmers, new learners and experienced community members. Communities of practice consist of individuals who are involved in collective learning and production processes on a proposed task (Aparici et al, 2019). Participation is open to anyone interested in open source technology. Voluntary contributions are the main energy of the communities, no matter how small. Digital media platforms such as mailing lists, wikis and websites are shared space for collaboration and coordination (Berdou, 2011). Collaboration refers to the activities in open source communities such as sharing software, designs, reporting a bug, commenting about products, replying to questions and so on.

is a result of collaborative production in which peers share their ideas and techniques. It is productive because it is a creative activity. It is fun because it is enjoyable, and producers learn new things when producing. It is labour because their creative activities are exploited by firms that use open source software and designs in their hardware goods. Creative activities consist of software production and design in open source communities rather than the uploading of photos, making comments or playing a game. Furthermore, open source communities do not sell mailing list of forum content of to third parties. In productive fun labour, users' or producers' private data are not commodities sold for ad companies, instead the products of their labour are appropriated by the firms.[10] Productive fun labour is a clearer term that explains the activity of hackers in open source communities, rather than unpaid labour, free labour or playbour. I use it in this thesis for the contributors of hackers or volunteers. I will give more details that support my definition of "productive fun labour" in the following chapters.

Up to this point, I have discussed how capitalist exploitation takes place in creative activities and free time. I argue that the capitalist system increasingly exploits creativity and the free time of producers. However, industrial capitalism has standardised and mass produced all cultural products. The culture industry has forbidden humans from playing an active role in the production of culture and ignored the role of social relations and autonomy of humans in creative activity. However, through social production, the capitalist system is provided with new opportunities to exploit the people's creative activity and free time. User generated content or unpaid labour can be commodified by social network platforms.

In a similar way. the digital game industry can benefit from the creativity of modders to lead to innovation. Capitalist exploitation spreads into most fields under contemporary capitalism. Even though capitalist exploitation seems difficult to avoid, Buzgalin and Kolganov (2013, p.506) point out that "the ending of the exploitation of creative activity can... only be the ending of (private) ownership of cultural values (intellectual property), and ... the ending of the relations of alienation and appropriation

[10] At this point, the privacy of users or user generated content on social network is commodified, but in open source communities, software or design as a commodity is appropriated. Data in open source communities is not mostly sold. Open source supporters usually make a living from providing a service to open source software users or from the fund offered by the firms, Most contributors are volunteers and are not paid, but the products developed by their voluntary labour create surplus value in the market. In other words, their labour is productive labour.

(in their economic sense) in the world". They also add that there are some international social movements and networks that reject (private) intellectual property, for example, the pirate party and international projects have worked on policies such as the open access model and so on. It is time to explore peer production and free open source communities.

The Issue of Peer Production and Free Open Source Communities

Peer production is described as a new production model based on the sharing of resources and it has a strong relationship with the concept of commons. Thus, Yochai Benkler (2006) uses the definition of "Commons-Based Peer Production" (CBPP) for the new type of production in order to address the strong relationship between peer-to-peer production and commons.[11] Bauwens (2009) claims that peer production has three interlocking characteristics: free access to the raw material, the opportunity for participation in production, and commons-based production. These characteristics highlight the interactivity of internet users.

The Free Open Source Software (FOSS) movement has been one of the most popular projects built on CBPP (Benkler, 2006). Part of the wider hacker movement, FOSS has represented an evolution in the software industry since the beginning of the 1970s. The movement consists of online communities producing software code and sharing them with peers. FOSS communities have struggled with proprietary companies by developing FOSS as an alternative software product that can be changed, modified and shared by users. This means that, on the one hand, business people might capitalise on the internet through the commodification of information, exploitation of users' labour or data and surveillance of users' activities. Collecting users' data without permission and using these data for the purpose of surveillance represents an invasion of users' privacy. Users are unable to stop surveillance on the internet if they use closed source software, which prevents users' access to source code. In this way, users cannot play an active role in the extension of the realm of freedom on the internet, but rather become obedient followers of the rules of corporations (Scholz, 2013; Fuchs, 2014a; 2014b). On the other hand, hackers struggle against technology cartels that keep source code of software closed, to control flows of digital goods on the internet, and hackers further support open source policies for the freedom of internet users.

[11] Commons-based peer production is a production model based on a collaborative and decentralised structure where individuals cooperate with each other without managerial commands.

They argue that FOSS provides users with an alternative production (Benkler, 2006). Users can become part of FOSS communities, where many participate in the production and distribution of software and are able to modify the existing products according to their needs. This production model, it is argued, is more "democratic" than that of the proprietary company, because FOSS enables users to become active participants in the production process, rather than a mere consumer. Creativity is the most important element in FOSS production. Edison Bicudo (2019, p.134) claims that "the notion that code is the expression of personal capacities, skills, and talents" is shared by most programmers. Without the creativity of developers, it is impossible to develop software. He adds that "code is not only a highly formalized text aiming at certain functionalities; it is also the backstage that can at any time become the main stage on which the programmer is surprised" (ibid). Code is not just a functional product; it is also an object of beauty. Creativity, in this sense, is a significant part of hacker culture (Himanen, 2001). Whilst Bicudo has an overly individualistic way of looking at hacking and programming, I would argue that it is crucial that the social institutions are seen in context of making possible the productivity of software programmers.

Production of FOSS is mostly seen as free time activity, rather than that of work time (Aparici et al., 2019). Hackers are generally organised in online communities to manage the production of software (Stallman, 2002; Jordan, 2008). These communities mostly consist of numerous volunteers who give up their free time and productive fun labour in the production of software. Berdou (2010, p.20) asserts that open source communities have a couple of basic characteristics: "program of meritocracy..., mobilizing action and a common basis of participation... and the tools and techniques for community management". The community consists of participants who have a similar motivation to create open technology but have various levels of skill and experience. Open source communities are made up of two main groups: developers, mostly paid, and volunteers, who are not paid (Berdou, 2010; De Bruijn, 2010). Developers are a small group and stand in the centre of the community, while volunteers are the majority of the community but at the periphery. Developers are active contributors who spend more time in communities than that of volunteers. They usually have considerable skills and experience in the production of code. Even though volunteers are mostly accepted learners observing the discussions and conversations on mailing lists or online forums, they also provide the extra labour necessary for the

commons; they serve to document, check the technical aspects of development, provide accessibility, translation, and improve the overall quality of technology (Berdou, 2010). In this sense, volunteers' activities can be defined as productive leisure time activities, which include "the resolution of problems, the reuse of goods, the coordination and construction of synergies, the search for experiences and the request for information" (Aparici et al., 2019, p.201).

While developers develop a strong interaction at the centre, volunteers can have a loose connection and strong autonomy in the periphery. Once volunteers get more skills and experience in the development of software, they can sometimes move to the centre from the periphery. In this way, contributors, can make a living from the contribution they provide in the community, instead of remaining a volunteer. These co-developers then can benefit from the fund provided by the firms that develop a business model based on open source policies (Mansell and Berdou, 2009; Berdou, 2010). Thus, volunteer activity can be exploited by firms in the name of an open source business model. The labour might be said to serve the accumulation of capital in favour of companies, whereby the commons created by volunteers' free time activities is appropriated.[12] In other words, the firms "extract revenue from collectively produced public goods" (Berdou, 2010, p.53).

Firms also manipulate the production in open source communities in the name of economic interests (see Berdou, 2010). Firms can force co-developers, who are mainly paid, to create a product that serves firms' interests in the market. Hackers may need to work on a task decided by firms, instead of working on a task they like. Paid hackers can lose their autonomy in open source community since firms can decide where they should focus on. Furthermore, companies may not allow co-developers to access its development tree (Ibid). The hiring of key contributors has a significant effect on FOSS communities and the dynamics of collaboration (Ibid). The firms can damage the social relations between contributors. The intervention of the firms in FOSS communities can pose a threat insofar as to radically change the communication model from bottom-up to top-down. Manipulative intervention in open source communities, therefore, can reduce the creativity that arises from community interaction since the firms can dictate their agenda and developers are unable to decide on what tasks they

[12] Commons means resources are shared by all.

perform (Ibid). This problem fundamentally derives from the tension between the logic of the market and the logic of peer production. Berdou explains this tension.

> On the one hand, there is the logic of the market economy in which people are driven by the desire for profit, transactions can be mapped by visible flows of money and capital and resources are scarce. On the other hand, there is FL/OSS, which is seen as operating in the domain of the gift economy, in which individuals are driven by enlightened self-interest and the desire to contribute to the creation of a common good from which they themselves benefit (Berdou, 2010, p. 76).

Berdou, also, (2010, p.120) claims that "FL/OSS software is a valuable commodity... FL/OSS as a commodity is the creative energy and productivity of FL/OSS contributors". As I discussed above, the exchange value of a commodity creates surplus value that subsequently turns into capital (Marx, 1990). In this sense, I argue that FOSS might lead to capitalist exploitation in open source communities since FOSS products as commodities can be sold in the market, but most contributors are not paid. FOSS production is mostly based on the interaction and collaboration between peers. However, social relations in FOSS communities can be ignored by the firms and co-developers. Software production is usually limited to the production of code and algorithm (Raymond,2001). In this sense, I ague that collaborative relations fostering creativity can be a relatively unimportant feature of community-based production. Peer production is not the production of a small number of very talented and skilled developers (see Benkler, 2006). The power of peer production comes from the network of a great number of volunteers who make a contribution (see Berdou, 2010). Some make more, some make less, but in total, a considerable amount of productive fun labour of volunteers is used in the FOSS production. This makes peer production meaningful to people supporting social production, rather than proprietary production managed by a small number of professionals. I now want to incorporate these concepts and ideas in a discussion about hardware hacking.

Hardware hacking is a relatively new phenomenon that involves hacking into hardware goods. Hardware hacking activities are made up of a range of cultural practices such as "crafting, tinkering, and other do-it-yourself (DIY) activities" (Powell, 2012, p.697). It is argued that hacking practices offer users opportunities to create new forms of technological citizenship, "based on better knowledge about how things work and increased abilities to take part, repair and reconstruct the devices that increasingly mediate and facilitate our communication" (Ibid, p.705). It is also argued that hardware hacking provides individuals with a broader range of opportunities for the

manufacturing of hardware (Rifkin, 2014; Pearce, 2012). Both production of hardware designs and the manufacture of hardware are central features of FOSHW community activity, in which a considerable number of hackers, developers, designers and volunteers give up their productive fun labour to the communities in the name of peer production. FOSHW projects such as Prusa 3D printers and Arduino microcontrollers are receiving more attention in the market.

Even though capitalist exploitation has been discussed on social network platforms, in the games industry and in FOSS communities, FOSHW becomes a new form of open source community. We need to analyse and understand 'productive fun labour' in FOSHW, as the business model of FOSHW is mostly concerned with the exploitation of labour and creativity of hackers.

The Internet and Intellectual Property Rights

The invention of the internet was a crucial milestone in the history of mass communication and in terms of flows of information, establishing a communication medium that has allowed open source software and hardware to develop rapidly. Manuel Castells also argues that whilst traditional mass communication tools are mainly based on a vertical communication process, in which the message is sent from one to many such as radio, television, and newspapers, the internet is a new type of interactive communication, characterised by the sending of messages, from one-to-many to many-to-many (Castells, 2013). In this sense, the internet is a network connecting most computer networks. By network, I am referring to the idea of a cluster of interconnected nodes – and the internet is a network of networks. Networks become communicative structures, so information flows between nodes. The purpose of networks is to carry information around the internet structure extremely quickly, enabling social actors to cooperate and compete (Ibid).

Similarly, Fuchs (2008, p.139) describes the internet as having specific characteristics, such as many-to-many communication, interactivity, globalized communication and cooperative production. He claims that the many-to-many communication process has demolished the vertical communication process. The horizontal communication process has established network platforms based on the decentralised structure of the internet (Fuchs, 2008). Castells (2013) notes that this structure enables the individual to become a user who can play an active role on the network platforms, instead of simply being one of an audience that consumes mass

communication content generated by a bunch of professionals. In this way, the most dynamic element of the internet has indeed become those internet users who play an active role in the creation of a network of computers. Since the 1980s users have created many online communities, based on network platforms; in other words, online chat tools, e-mail lists, social networks, and others (see Lake, 2009) for conversation and discussion. Castells (2013) calls the internet a mass self-communication tool, in order to separate the internet from the traditional means of mass communication. It is a mass communication tool because it allows users to reach a potentially global audience through peer-to-peer networks. It is also a self-generated, self-directed, and self-selected tool for users. This has important implications for networked forms of peer production, such as FOSS and FOSHW.

There is a strong relationship between the rise of the internet and the rise of peer production. The internet, on the one hand, provides users with an important platform to create online communities driven by shared values and ideas. Through the structure of the internet based on distributed and decentralised environment, users organise the contributions of hundreds of or, in some cases, thousands of contributors around the world. Open source communities benefit from the principles of open access, peer review and decentralisation to mobilise contributors in software production. The internet transcends the confines of space and time and the traditional knowledge communities evolve into online communities with more members and greater diversity than the old ones (Berdou, 2010). Open source communities have a highly creative atmosphere supported by digital platforms such as mailing lists, forums, websites, video conferencing tools and so on. These communities attract more contributors to their activities, which can include learning, sharing, collaboration and so on (see Raymond, 2001; Stallman, 2002; Berdou, 2010). There is however increased commercialisation of the internet. Digital companies and social media corporations become big players that watch users' activities and commodify them for their economic interests (Fuchs, 2014a; 2014b).

The commercialisation of the internet has a great impact on open source communities. As I argue above, firms that become partners or contributors to open source projects can sometimes manipulate the communities in favour of their own interests. The vertical communication model in companies can damage the structure of open source communities, where horizontal communication enables users to contribute their free time for open source projects. The internet is called "a dilemmatic space

where non-profit peer-to-peer collaborative practices and open source networks converge with platforms that seek the economic benefit from hierarchical approaches that establish clear vertical power structures between digital companies and their users" (Aparici et al., 2019, p.205). The internet is a platform based on an antagonistic social formation, which on one side deepens exploitation and alienation, while on the other advancing potential for creativity and liberation (Fuchs, 2014b, p.328).

Even though capitalist exploitation has had detrimental effects on the internet (see Fuchs, 2014a; 2014b), I argue that people can still effectively benefit from the internet to mobilise contributors in the creation of open source projects. Through online platforms, hackers put their creativity and capacity into practice. The free time and labour of hundreds of volunteers are organised through interactive digital tools. As I argued previously, creativity, in this specific sense, can be possible with co-creativity. The internet as a mass-self communication tool enables users to become active players in the organisation of collaborative platforms. Collaborative communication between hackers becomes the most important element in FOSS and FOSHW communities. Without the internet, it could be impossible to mobilise these great number of hackers who give up their free time and productive fun labour for FOSHW projects (see Berdou, 2010). Yet, without the unpaid labour of hackers, it could be impossible to create the internet itself (Hesmondhalgh, 2010). Now I want to focus on intellectual property rights and the relationship between creativity and capitalist exploitation.

Intellectual property is the material embodiment of mental creation and includes names, symbols and images; artistic works and literature; and inventions in commerce. The World Intellectual Property Organisation (WIPO) defines intellectual property rights (IPR) as property rights that enable the holders of patented or copyrighted works to take advantage of these works. Intellectual property consists of two main categories: industrial property, which contains patents for industrial designs and geographical indications, inventions and trademark, and copyright which involves literature and artistic works, movies, music and television programs. (Wipo.int, 2016) It is claimed that the central purpose of intellectual property rights is to protect the rights of creators or inventors and thereby the interests of society, by supporting creators and inventors; they should be able to benefit from their works, make a living and maintain their investment (Ibid). However, Drahos and Braithwaite (2002, p.55) argue that the laws of intellectual property rights are effectively used as a weapon by "knowledge cartels" to keep flows of knowledge under control and to maximise profits from copyrighted and

patented knowledge. In contrast, certain theorists have argued that sharing information and knowledge is not a crime and should not be treated as an unlawful act (see Lessig, 2004; Benkler, 2006, Rifkin, 2014). Indeed, they argue that sharing is one of the most significant social elements serving to promote the interactions between people promoting collaboration and other social goods, for example, peer production. Drahos and Braithwaite (2002) argue that copying or imitation is central to the process of learning and acquisition of skills. We can see that overly stringent policies of intellectual property rights undermine people's ability to gain access to knowledge, thereby eroding their creativity.

The free and open source movement has become more politically oriented since the beginning of the 2000s, with the expansion of intellectual property rights, thought to undermine creativity and innovation (Berry 2008, p.xii).[13] A key exemplar of this was given in 2013 when Aaron Hillel Swartz, an American Internet hacktivist, creative commons activist, computer programmer and writer, killed himself shortly before his trial for downloading journal articles from the JSTOR digital library of the Massachusetts Institute of Technology's (MIT) computer network (Pengelly, 2014). Prior to committing suicide, he was facing up to 50 years in prison for allegedly downloading academic papers as PDFs from a server. Swartz was accused of using MIT's computer network to automate the download of millions of PDF documents from JSTOR (Ibid). He wanted to share these documents and academic journals on the internet in the name of the free flow of information, one of the central elements of the *Guerilla Open Access Manifesto* that he penned (Swartz, 2008). However, open access, understood by Swartz as "freeing" information, also constituted a severe threat to the companies whose revenue was based on intellectual property rights (IPR). For example, the market in the three sectors of "technical and medical", "educational and scientific" and "trade" IPR, was estimated to be worth $248 billion (Wipo.int, 2018). This shows that the capitalist system can seek to extract profit from intellectual activities under the current rules of IPR. Thus, capitalists will naturally seek by any means to avoid diminishing profit rates in the marketplace. The distribution of knowledge can be restricted by copyright holders through the laws of intellectual property rights since it

[13] The Creative Commons was a very successful attempt to transfer the principles of sharing software source code into the cultural sphere through the creation of copyright licenses explicitly creating for creative works. For example, sharing images, photography, music or video that could then be used and drawn upon in subsequent, but similarly licensed, works (Berry 2008, p. 22).

can be difficult to gain money from free flows of knowledge. It is important to note that copyright holders may not be the creators of intellectual properties. Creators can sell their innovative or creative knowledge to "knowledge cartels" who commodify this knowledge and make profits from it. (Drahos and Braithwaite, 2002, p.15). Even though the restriction of information distribution has a detrimental impact on the development of creative activities, copyright holders give priority to the profits they extract from copyrighted information (Ibid). This shows how capitalism protects the interests of a small number of copyright holders, rather than considering greater benefits to society.

This system is called "information feudalism" by Drahos and Braithwaite (2002), whereby a small number of information cartels manage the distribution of knowledge out of pure economic interest, rather than the public interest. Knowledge assets are transferred from the intellectual commons to private hands (Drahos and Braithwaite, 2002, p.2). Accordingly, IPR can be used as a bridge to transfer creative activities to capitalist interests. I argue that companies may ignore the potentiality of open access on creativity, because they are more focused on the economic potential of innovation for their own interests.

It is important to note that the contributors of FOSS and FOSHW also benefit from IPR to easily distribute software and designs. Hackers make use of the General Public License (GPL), also called a copyleft license, Creative Commons (CC) and open licenses to support the distribution, copying, and modification of software source code, and provide legal protection for digital commons-based projects (see Berry, 2008, 114-115). The GNU GPL was indeed created to support the free flow of information, in opposition to other licences that restrict the flow of information. RepRap and Arduino projects, as well as FOSHW use GPL and CC licenses. Erik De Bruijn, one of the co-developers in the RepRap community, claims that open licenses enable individual developers "to prevent appropriation of their work" (De Bruijn, 2010, p.9). The open licenses mean that contributors do not need to ask for permission when using existing open source products in the development of their software products. The open license also "reduces transaction costs, the barriers to contribute and duplication of effort" (ibid). Bruijn also adds that copyright law covers "implementations of ideas, and not the ideas themselves" (ibid). In other words, the license can be used for copies of the design file and design documents, rather than the design itself.

I now want to briefly give an overview of the RepRap and Arduino projects as empirical cases of FOSHW. The RepRap 3D printer is a self-replicating machine, capable of printing most of its components. In this way, the users of this machine- with access to raw materials- can print new self-replicating machines for their friends and neighbours without the need for huge machines and factories. RepRap is a free open source desktop machine. Therefore, users can freely access designs, software, and information regarding the machine on the RepRap website. The claim of the RepRap community is to create "wealth without money" through a self-replicating machine. This claim seems very radical when taking the process of production, distribution, and consumption of goods in capitalism into account, because desktop 3D printers allow people to manufacture goods at home for use value, and not exchange value. Producers of hardware goods also become consumers of hardware goods: prosumers. Their claims to creating wealth without money through self-replicating machines and are central reasons why I have chosen the RepRap community as an empirical case. These claims lead to rich discussions, including on themes deserving of analysis, such as free time and fun (see, for example RepRap.org, 2018a).

Arduino is also an important free open source hardware community producing microcontrollers for robotic devices. Significantly, the Arduino community freely shares the design and software of the microcontrollers on its website. Microcontroller boards are also sold on the website. The free open-source microcontrollers become valuable tools for hobbyists, makers, and students to build electronic and robotic devices of their own since Arduino boards are relatively cheap and simple. The boards are made by official manufacturers who make a royalty payment to the Arduino company (formed by the founders of the community), but there are also some manufacturers who do not make payments even though they use the Arduino trademark on their clones. The counterfeiting of Arduino boards is, therefore, one of the hottest topics in the community. Otherwise, revenue from the sale of Arduino products is controlled by the company, and the rules of the community are decided by the company owners. I have selected the Arduino community as the second empirical case because it provides me with important details on corporate intervention in the FOSHW community.

The topics discussed on the RepRap and Arduino mailing lists are not exactly the same. Although there are common topics, such as open source and

license, there are also different issues, such as customisation and fun for Reprap, cloning for Arduino. Nonetheless, both provide substantial amounts of data for my thesis. I have also chosen both the RepRap and Arduino communities because they have a great number of international contributors on their mailing lists, where contributors give up a significant amount of free time and creativity.

In this thesis, I also show that strong tensions can emerge among hackers in both communities, over the concepts of "commons" and "market". Hackers may form different ideological tendencies in open source communities, and we can discern two main ideological views in competition with each other. When I have looked at the data coming from mailing lists and interviews, I have realized that there are two main groups that struggle around what I will call the "logic of the market" and the "logic of the commons". This does not mean that all hackers have an ideological orientation and are supporters of communitarian or libertarian ideas, rather they situate themselves around these debates. I have borrowed the concepts of communitarian and libertarian defining the political orientation of hackers from Karsten Weber (2014). "Communitarians", on the one hand, support the idea of commons to create an alternative ecosystem whereby the rules of capitalist production do not apply. "Libertarians", on the other hand, do not accept cartel regulations, instead advocating for the commercialisation of open source products and a much fairer capitalist system (Ibid). I then applied a thematic analysis to the data from both mailing lists and interviews depicts further supporting evidence of an ideological difference between hackers in both communities.

Thesis Structure

Chapter Two discusses the theoretical framework that informs my analysis in this thesis. I begin by analysing the concept of hyper-exploitation. I explore capitalist exploitation in and of social production. In the second section of the chapter, I focus on the emergence of CBPP, and examine how mass communication has been turned into mass self-communication, enabling users to play an active role in the production of digital media content rather than being a passive audience that consumes mass media content. I then highlight the reappearance of the concept of commons in the digital field, alongside the rise of the internet, and address the opportunities and challenges of CBPP using a Marxist framework. I also explore how hyper-exploitation takes place in FOSS communities. At the end of the chapter, I examine the main characteristics of FOSHW.

Chapter Three explores the various approaches of my wider method. I begin by discussing RepRap and Arduino communities having communication platforms such as websites, forums and mailing lists from which I have collected primary source data. I also outline the interviews I have carried out with the members of developers' mailing lists. Three different interview types have been used in my research: online video interviews, face-to-face interviews and email interviews. In the next section of this chapter, I apply thematic analysis to the data I have collected from RepRap and Arduino mailing list archives, and the interviews. I also explain the example case approach and why it is significant for my research. Lastly, I apply corpus text analysis for the mailing list archives with 5.92 Mb (2.92 Mb for Arduino and 3.13 Mb for RepRap) of Text Document (txt) data. I briefly explain how I benefit from AntConc, a corpus analysis tool, to clean the data and determine the key concepts on the mailing lists on which to carry out thematic analysis. At the end of the chapter, I highlight the significant ethical issues I have faced during the research and how I have dealt with them.

In Chapter Four, I discuss how hacking as a concept has taken on new meaning, highlighting a significant turning point the history of hacker movement: the shift from programming proletariat, free software developers and crackers, to hacktivism and free open source hardware. I clarify the role of hackers in the digitation. I begin by discussing the FOSS movement that has led to discussions on freedom of technology users. I also highlight the issue of open source communities and the issue of intellectual property rights. I discuss the relationship between the FOSS movement and proprietary corporations that provide funding for open source communities in return for using open source products in the hardware they produce. Lastly, I focus on the definition of free open source hardware (FOSHW), which represents a relatively new stage of hacking culture, and the opportunities and challenges of FOSHW.

In Chapter Five, I focus on Replicating Rapid Prototyper (RepRap) as an example case. The chapter consists of two sections: background of the RepRap project and analysis of the RepRap community. I begin this chapter by discussing how the RepRap project emerged, making reference to those who have led the community. RepRap is a self-replication machine that produces most components of itself made of plastics. At this point I discuss the potential of free open source self-replicating 3D printers in creating desktop manufacturing tools and manufacturing tangible goods in people's homes. In this section, I also mention the loaner program developed by the community to strengthen a solidarity network which allows peers to share components of the

machines. In the second section, I analyse the data collected from the RepRap developers' mailing list and the interviews. I provide details of the demographic backgrounds of interviewees, that give significant clues to the general demographic background of the RepRap community. I also discuss certain vital themes: the issue of open source, the issue of self-replicating, the issue of customisation, the issue of intellectual property right tools, fun in the RepRap community, the structure of the organisation, and collaboration in the RepRap community; all of which feature significantly in mailing list discussions. In this section, I outline the tensions between RepRappers arising from ideological differences surrounding concepts of "commons" and "market", and between communitarian and libertarian.

In Chapter Six, I start by discussing how the Arduino project emerged, and why Arduino is a popular project in the FOSHW movement. I also highlight the opportunities and challenges posed by the Arduino project and community. I briefly mention the history of Arduino and the disagreements and conflicts between the founders of the Arduino Company. There have been two companies using the name of Arduino in two separate countries: Arduino LLC, arduino.cc in the USA and Arduino SLR, Arduino.org in Italy. I discuss the reasons why Arduino founders created these different companies even though they had the same goal at the outset. I also highlight the asymmetric relationship between the Arduino company, run by a small number of project founders, and the Arduino community, which includes thousands of members who mostly contribute to the project voluntarily. In the second part of this chapter, I analyse the data I have gathered from the Arduino developers' mailing list and the interviews conducted with members of that list. I also choose particular key themes: the issue of open source, the issue of Arduino clones, fun in the Arduino community, the issue of intellectual property right tools, sharing in the Arduino community, the structure of the organisation, collaboration in the Arduino community. Additionally, I highlight through thematic analysis the ideological differences among hackers, arising from the tensions between the commons and the market.

I conclude with Chapter Seven, tying together the main themes of the thesis in relation to the research questions outlined at the start. I summarise each chapter, concentrating on the scope of each chapter and my analytical findings. I then explore future avenues in the understanding of the FOSHW movement, the opportunities and challenges of RepRap and Arduino, and the tensions between the principles of the commons and the market. Moreover, I discuss how this thesis makes a contribution to

the field of digital media and digital humanities. Lastly, I make some suggestions for researchers who seek to work in this field.

Chapter 2: Literature Review

This chapter details the major theoretical and empirical sources that inform my research project. The aim is not to provide comprehensive coverage of the academic literature but rather to give a sense of the major contours of the contemporary debates in the relevant fields. Firstly, I look at the concept of hyper-exploitation in the digital field. Secondly, I turn to the nature of peer production, the mode of production used by the hacker communities. The chapter provides a theoretical framework for analysis of the empirical cases. It focuses primarily on the modes of production, where technology is developed, and the role of social relations in the production process. However, I will also take the impact of technology into consideration in the development of social relations.

The new production model relies on peer-to-peer networks, which are distributed networks free of strict hierarchical and centralised control. Peer-to-peer systems allow individuals to share files and knowledge/information, without having to obtain permission, by means of decentralised networks (Benkler, 2006). The term commons-based peer production (CBPP) accurately defines the production process of free/open source projects, but CBPP does not just consist of Free Open Source Software (FOSS). CBPP is a mode of production that is actively used in the field of, for example, digital encyclopaedia [e.g., Wikipedia] (see Tkacz, 2015), house design, farming, open street mapping and hardware design (P2Pfoundation.net, 2017). In order to understand how peer production is practised, the characteristics of this new type of production mode must be clearly explained. The relationship between proprietary companies and CBPP is the critical issue in open source communities, since proprietary companies are the dominant figures in contemporary capitalism giving rise to social inequalities (see Van Dijk et al., 2018). My research investigates the exploitation of free time and creativity in CBPP, and particularly with respect to FOSHW.

Hyper-Exploitation of Free Time and Creativity

Capitalist exploitation has been broadly outlined in Chapter 1. In this chapter, I focus on how this exploitation occurs in the digital field and social production. As I have mentioned, capitalist exploitation in the creative business is mainly based on the appropriation of commons created by volunteers. Capital can be accumulated through the extraction of value: “the appropriation of wealth produced and socially accumulated by labour-power” (Hardt and Negri, 2018, p.418). The internet and digital technologies can

facilitate collaborative and cooperative activities in the organisation of social production. These technologies, however, can also allow capital to form a new regime of accumulation. Hardt and Negri add,

> When we enter in the current phase of capitalist development characterised by cognitive and social production, the social cooperation of labour is enormously enhanced, immersed as it is in a set of communicative networks and digital connections that increasingly permeate all the industrial assets, services, agricultural systems, and all the other figures of the economic organisation of society. Capital is, in fact, increasingly valorised by cooperative social flows in which muscles, languages, affects, codes, and images are subsumed within the material processes of production (Hardt and Negri, 2018, p.416).

All activities in communities, in other words, digital labour, are integral to collaborative production, which initially requires a communicative networking. In this way, people contribute their labour, time and energy to the creation of products through this communicative network. Hardt and Negri add that:

> Today production is increasingly social in a double sense: on one hand, people produce ever more socially, in networks of cooperation and interaction; and, on the other, the result of production is not just commodities but social relations and ultimately society itself (Hardt and Negri, 2017, p.xv).

Social relations are not just the result of production, they play a vital role in the production process. Interactive communication based on digital networks enables volunteers to promote their creative skills and become part of the production process. Social production renders meaningless the differences between producers and consumers, and the concept of prosumer emerged in social production, to emphasise collaborative production between humans who simultaneously produce and consume (Roberts and Cremin, 2019; Fuchs, 2014b, 2015).

As has been argued, the boundaries between work time and free time in contemporary capitalism are no longer quite distinct.[14] One of the most important features of contemporary capitalism is that it can extract value not just from the work time of workers, but also from the free, yet productive leisure time of humans, in which people voluntarily participate in collaborative production (see Hesmondhalgh, 2010). Work "spread across a much wider range of activities, many of which are not even identified as 'work', but rather presented as an expression of 'desire' or 'passion'" (Boltanski and Esquerre, 2016, p.54). If a production activity may not be defined as a form of work, e.g.,

[14] As I explained in Chapter 1, work time refers to time spent on paid work. Free time is the time spent on self-realisation.

leisure activity, it can be assumed that capitalist exploitation is unlikely to occur. This is a controversial argument, since productive leisure time now can play a significant role in social production, and people who give their leisure time to collaborative production are not paid. It is difficult to draw a definitive line between work time and leisure time. Bahar Kayihan (2018, p.635) suggests that "neoliberal capitalism has turned free time into labour time and makes cultural labour appear as play, fun, and enjoyment. Increasingly, we no longer realise that we are workers and are exploited, because labour feels like fun". The relationship between labour and fun shows that productive leisure time is not only an important part of the labour process, but also becomes a significant element of capitalist exploitation. Therefore, I propose "productive fun labour" to define the activity of social production in the digital field.

Vasilis Kostakis and Michel Bauwens define exploitation of leisure time as "hyper-exploitation": "Under this regime of cognitive capitalism … use value creation expands exponentially but exchange value only rises linearly and is almost exclusively realized by capital, giving rise to forms of hyper-exploitation" (Kostakis and Bauwens, 2014, p. 27). It is hyper-exploitation because "society is deproletarized, that is, wage labor is increasingly replaced by isolated and mostly precarious freelancers; more use value escapes the labor form altogether" (Ibid). Collaborative production becomes an object of capitalist exploitation. Kostakis and Bauwens (Ibid) add that "there is an increased contradiction between the proto-mode of production, which is peer production, and associated forms of networked value creation with the relations of production, which remain under the domination of financial capital". The concept of hyper-exploitation can help to differentiate the capitalist exploitation of productive leisure time, which is unpaid, from the exploitation of waged labour. On this, David Harvey asserts that:

> … a system of political economy based on the voluntary labour applied in commons-oriented peer production. What was initially conceived as a liberatory regime of collaborative production of an open access commons has been transformed into a regime of hyper-exploitation upon which capital freely feeds (Harvey, 2017, p. 81).

When Buzgalin and Kolganov (2013) define capitalist exploitation based on creativity, they point out that capitalists no longer buy labour power, they buy the creative potential of a person, but in the case of collaborative production it appears that capitalists no longer even pay for the creative potential. This is a regime of hyper-exploitation, since capitalists benefiting from voluntary labour no longer pay wages to producers. Kostakis and Bauwens (2014, p.27) claim that "the use value creators go totally unrewarded in terms

of exchange value, which is solely realized by the proprietary platforms". In addition, George Ritzer (2014, p.18) says that "in most cases prosumers are paid nothing by the capitalists who profit enormously from this arrangement… they earn far greater profits because instead of the pittance normally paid to workers, they pay the prosumer nothing at all". Ritzer compares hyper-exploitation with the exploitation of waged workers. He adds that "from a purely economic perspective, prosumers are exploited within a capitalist system and they are exploited to a greater extent than the proletariat" (Ibid). Ritzer's comparative analysis can be useful in defining the form of hyper-exploitation.

Hardt and Negri (2017, p.119) also assert that "capital captures value not only through industrial exploitation and through the time management of the organization of labour but also and increasingly through the extraction of social cooperation". Social cooperation is a relatively new form of capitalist exploitation, thus, the accumulation of capital. It shifts the main area of production from the factory to society. With this shift it can extend the exploitation of workers outside the factory, to the area of social production. Harvey (2017) points out that creative work is mercilessly commodified by cultural entrepreneurs and tuned into profitable commerce. The creation of value by voluntary labour and the appropriation of this sort of labour should be vital topics for scholars interested in debates about the role of "cognitive capitalism" and the question of the value of creative productivity and knowledge production.[15]

Hamid Ekbia and Bonnie Nardi have also created a new concept of "heteromation" to define the labour process in the peer production model. They claim that "heteromation is consistent with the labour theory of value; capital uses computing to extract low-cost or no-cost labour in networks to sustain the growth of profits" (Ekbia and Nardi, 2017, p.32). In this situation, many may not have job security, health insurance and past retirement age and still contribute to the process of production. Contributors essentially supply unpaid cognitive labour, which includes the creation of knowledge, software, designs, and communicative labour, which involves sharing a photo, personal news or the manufacture of data (see Ibid).

Knowledge, imagination, and ideas have significant use value in the production of technology. Human imagination and creativity are integral to the labour process

[15] Cognitive capitalism refers to an economic regime, in which cognitive or intellectual production, such as creative activities, science, arts and so on, play a key role in the accumulation of capital (see Moulier-Boutang, 2011).

(Harvey, 2017). Marx explains the importance of human imagination and creativity in *Capital Volume 1*. He asserts that "what distinguishes the worst architect from the best of bees is this: that the architect builds the cell in his mind before he constructs it in wax" (Marx, 1990, 284). The creative imagination is one of the most important characteristics distinguishing humans from other animals. However, the product of creative activity is increasingly enclosed, privatised and converted into a commodity through intellectual property rights (Harvey, 2017). The intellectual property rights regime puts humans in a difficult situation, in which they are estranged from the product of their creativity, the production process and their own nature as human beings.[16] Copyright holders decide who can have access to knowledge, which for Harvey is a part of the global commons (Ibid).

Intellectual production becomes collaborative as in creators share ideas and produce knowledge together. However, under the IPR regime, in some cases, creators themselves cannot share their intellectual products with anybody without the permission of copyright holders. Creators, therefore, can be alienated from what they produce, as this instead serves the interests of copyright holders. Indeed, creators are alienated from the production process itself, as not they, but copyright holders establish the rules of knowledge production (see Hesmondhalgh and Baker, 2011). Individual producers can also be isolated and limited by the IPR regime.

As I have argued, creativity is possible with co-creativity (Buzgalin and Kolganov, 2013). The restriction placed on interactive communication can lead to the death of creativity (see Drahos and Braithwaite, 2002). Furthermore, I argue that ignoring the role of social relations in collaborative production might cause commodity fetishism, since the product of intellectual labour, a commodity, mystifies social relations in collaborative production. Social relations constitute the main features of CBPP. Collaborative communication between peers makes peer production work. Open source products are not developed by a small number of talented hackers, but by the contributions of a great number of developers and volunteers. The real power of open source projects mostly derives from community-based production (Benkler, 2006; Bauwens, 2009). Social relations in communities of practice increase the creativity and productivity of individuals. The products developed by the communities therefore should not be seen as the products of particular developers who write code, since these developers benefit from

[16] Benjamin Coriat and Fabienne Orsi call the system supporting strong policies of intellectual property rights the "intellectual property rights regime" (Coriat and Orsi, 2002).

the synergy of the community when developing code or design. Open source projects should be accepted as the products of the commons, and all members of the community should be recognised as contributors to the projects, rather than listing solely software developers or hardware designers amongst the contributors; open source production does not just mean writing code.

Collaborative production, on the one hand, enables people to interact with other producers in the production process. Interactive communication has an essentially positive effect on the development of humans' creative skills. Yet, on the other, the results of creativity can serve capitalists in their accumulation of capital. There is an antagonism between collaborative production and capitalist exploitation. Hardt and Negri also add,

> …the varied forms that capitalist exploitation takes place in a wide field of domination (which includes axes of race and gender in addition to and in conjunction with varied forms of waged and unwaged labour) poses the need to *articulate* a range of existing struggles that challenge capitalist rule in different ways. (Hardt and Negri, 2018, p.441).

The exploitation of labour is the central part of the capitalist mode of production, but scholars can also take other parameters such as gender and race into account, for the critical political economic approach to technology (see Jordan, 2015). In this research, I will mostly focus on the exploitation of productive fun labour under capitalism. The themes of gender and race do not play a major role in this thesis, because I do not have sufficient data on the gender and race of contributors on the RepRap and Arduino mailing lists to be able to discuss this issue. However, I will provide details about the gender and ethnic background of interviewees, wherever the primary sources render this information.

So far, I have discussed the concept of hyper-exploitation and its impact on social production. In exploring the question of free labour with respect to social network corporations and that of productive fun labour in peer production, hyper-exploitation takes on great importance. I have proposed the term productive fun labour to analyse capitalist exploitation in FOSS and FOSHW communities. What does capitalist exploitation mean in collaborative production for me? It refers to a regime of capital accumulation in which producers are not paid for their productive fun labour. Capital is essentially accumulated by unpaid productive fun labour in favour of capitalists. Productive fun labour can be considered as free or leisure time activity. Increasingly, the social labour of multiple volunteers enables capitalists to make huge profits, and this can be detrimental to collaborative production (which, after all, claims to benefit society). It might be expected that productive fun labour should serve a fair system in which humans

collaboratively produce goods to satisfy their needs, but productive fun labour in some cases can be exploited. In this scenario, capitalists, do not pay wages to producers because the production process is accepted as a creative activity that occurs in free or leisure time.

There is also a debate about whether free time activities can be seen as labour that produces the value and indeed, the surplus value or not. For example, Kaan Kangal asserts (2016, p.7) that "unlike the user activity on the web, the labor power owned by workers is sold to the capitalist as a commodity. The labor of the worker produces the value, for which he is paid, and the surplus, which is appropriated by the capitalist for free". However, if a product, material or immaterial, has an exchange value in the market, and the labour involved in producing the commodity creates surplus value appropriated by capitalists, this clearly is capitalist exploitation.[17] It does not matter whether the production process takes place in work or leisure time. If capitalists do not pay wages to labourers, this is hyper-exploitation because unpaid producers are more exploited than waged workers. As long as productive fun labour is exploited, commercialisation on the internet spreads to CBPP projects and communities. Capitalism can retain the use of a voluntary labour force in the accumulation of capital, as long as resistance to hyper-exploitation does not occur in said communities. Hackers supporting communitarian ideas object to the use of knowledge commons for commercial purposes. I will discuss this issue in Chapter 5 and 6 in more detail. But now, I will focus on Commons-Based Peer Production (CBPP) and Free Open Source Software (FOSS).

Commons-Based Peer Production (CBPP) and Free Open Source Software (FOSS)

The structure of the internet, alongside technological developments in the digital field, provide individuals with new opportunities for collaboration and sharing activity. For one, the CBPP mode emerged on the internet. Yochai Benkler defines the CBPP mode thus:

> …the networked environment makes possible a new modality of organizing production: radically decentralized, collaborative, and nonproprietary; based on sharing resources and outputs among widely distributed, loosely connected individuals who cooperate with each other without relying on either market signals or managerial commands. This is what I call "commons-based peer production" (Benkler, 2006, p.60).

In order to understand the concept of commons-based peer production, the meaning of digital commons first needs to be explained. Sharing is another contested concept with

[17] İt does not matter whether paid labour or unpaid labour

respect to this mode, because it is not clear what the concept of sharing involves in this context. Furthermore, networks and communication play an active role in peer production.

Digital commons (or information commons) mainly refers to the creation and distribution of intangible goods on the internet. Tim Jordan (2015, p.24) claims that "the information commons means building information environments that are distributive and whose guiding principle is use and access to information, and the making of further information, for all in those environments". Online communities play a leading role in the formation of the infrastructure of digital commons, and productive fun labour is the central element of online communities for the production and distribution of digital goods. The members of communities are also the contributors of projects integral to peer-to-peer networking. Interactive communication permanently raises the creativity of the members of communities (Casali, 2017). Moreover, the infrastructure of the digital commons is slightly different from that of the institutions of the commons, which rely on nature and community (not online community) in terms of production and consumption of resources. The digital commons is fundamentally based on abundance, as opposed to scarcity (Bauwens and Iacomella, 2012), since intangible goods can be reproduced and distributed on the internet at the same quality and at low cost (see Benkler, 2006; Rifkin, 2014).

Sharing, however, is a significant aspect of peer-to-peer production in the copying and distribution of intangible goods. Although sharing is mainly defined as an act of consumption, it is also a vital practice in the production process (Schor, 2014). People share their knowledge, experience and labour on network platforms in order to participate in the production of a wide range of projects. Sharing in this mode of production indeed refers to the process of production itself, as sharing activities, such as sharing ideas, code, designs, suggestions and so on, are vital in this production model. This model is also called a "sharing economy" (Puschman, 2016), predicated on the sharing of products and services among peers. However, Bauwens (2005) states that peer production does not directly provide an income for its producers, because peer production produces use-value of intangible goods.

Nonetheless, sharing is a useful activity for online corporations as they make a considerable amount of money from users' activities on the network platforms. According to a report, Facebook's average revenue per user (ARPU) is $7.26; Snapchat's ARPU is $2.12; and Twitter's ARPU is $5.68 (Rodriguez, 2019). It is clear that sharing activities

on these network platforms do not refer to peer production, but instead serve the commodification of data and "communicative capitalism", a concept developed by Jodi Dean to identify commodification of user activities on network platforms (Dean, 2005). Consequently, sharing activities have different meanings in the commons projects and private platforms. Sharing practices in CBPP emphasise the freedom of the internet and digital culture (see Stallman, 2002; Lessig, 2004), while sharing activities on the platforms of digital corporations underline the exploitation of users' activities and social relations (see Dean, 2005; Fuchs, 2014a).

Lastly, the network is another essential element of the CBPP model alongside commons and sharing. Castells (2013) states that the internet is the network of computer networks, creating the structure of a new society. The network society referred to by Castells consists mainly of personal and organisational networks supported by digital networks. Power in the network society refers to communication power, and resistance to power in the network society is also made possible by communication power based on networks. Social movements can create alternative networks for their counter-power. I argue that the possibility of the creation of alternative networks on the internet might represent a critical historical opportunity for internet users, in terms of being a part of digital production. Peer production is partly a fruit of the communication counter-power strategy. Richard Barbrook (2003) notes that software, films, music and books have been gradually transferred into digital products. People mostly do not buy physical copies of these products, but instead download them, either paying or for free.

CBPP is, like post-Fordism, a production mode mainly based on information and communication technology.[18] But both are accepted as distinct production models (Benkler, 2006; Bauwens, 2009; Rifkin, 2014). Peer production has some specific features in terms of production, distribution, management and business. One of its most interesting features is that the production and distribution of goods are organised without the involvement of corporations. Also, peer production does not appear as a market-based production model. Bauwens argues that,

> Peer production is based on voluntary self-aggregation, and not based on the dependent wage relationship. It is only made possible because peer producers control their productive assets. These assets are both immaterial — i.e. the assembling of brain power through unpaid effort sharing — and 'material', in

[18] Post-fordism is a term of flexible production, based on the information and the service economies (Bell, 1999; Castells, 2010).

> the sense that peer producers must own or have access to computers, and must have access to the digital networks (Bauwens, 2009, p.123).

Peer production can be seen as a particular kind of organisation of work because it does not involve a centralised "boss", and few are paid directly. The argument is that users can easily gain access to the means of production (the computer and the internet) and voluntarily participate in the production and distribution of goods (Benkler, 2016; Rifkin, 2014). Peer production is mostly an activity of free and not work time. In the same article, Bauwens (2009) also states that peer production is mostly concerned with the use value of products, much less with the exchange value of goods. Thus, the accumulation of capital is difficult in peer production, as the lack of exchange value prevents goods from being sold. CBPP is interested in the use value of products, and the benefit to all users, rather than to information cartels. Phoebe Moore (2011, p.86-87) asserts that "the peer production protocol is composed by an ecology of interactivity that offers an alternative set of practices to capitalism. This is an ecology in which people are seen to be free to individually and/or collaboratively and cooperatively identify subjectivity". Interactive communication is one of the most striking features of peer production, offering an alternative production model to proprietary companies.[19]

CBPP has enormous potential in the democratisation of production, enabling the masses to be part of the production process. Democracy refers to the ability to access the means of production and to participate in the production process (P2Pfoundation.net, 2009; Rifkin, 2014; Fuchs, 2014a). Peers can play an active role in the creation of communities of practice on the internet, to help and collaborate with each other in the production of digital goods. Due to the fact that sharing digital products and communication with peers on the network platforms are cheap, thousands of members of digital communities can voluntarily share their experience, creativity, and capacities with one another in their free or leisure time without getting paid. This is a notable change in the processes of production, distribution, and consumption of digital products. In a proprietary company,

> managers have generally been successful in imposing structures on programmers that have eliminated their creativity and autonomy… covering such issues as training and education, structured programming techniques, the social organization of the workplace and careers, pay, and professionalism (Ensmenger, 2010, p.232).

[19] The proprietary model refers to a production model in which company that has hierarchical management produce closed source software in favour of capitalists.

A hierarchical system of management, which applies to most corporations, can lead to the end of worker autonomy (Ensmenger, 2010). But peer production is not based on mechanisation or standardisation; features that eliminate individual autonomy. Individual autonomy of peers, however, plays an important role in organised communities. This is a significant point because creativity co-exists with the individual autonomy of peers. Patricia Galloway (2012) asserts that hierarchical management can empty creativity and joy in the programming task.

There are some tensions in the relationship between the CBPP model and capitalism. Even though peer production can be accepted as an alternative political economy that has the potential to transcend capitalism (Bauwens, 2009), it might also be used as a new business model whereby capital is accumulated. This means that there is an exploitation of users' activities in communities.[20]

Some aspects of CBPP become blurred, and the roles of "use value", "exchange value" and "market" in the model are not altogether clear. Most producers working in peer production are not wage-labourers. Nonetheless, it is clear that producers can create value in the peer production process. But this might lead to confusion in the discussion of peer production and the creation of commodities and exchange value. For instance, Bauwens (2009) states that the CBPP model does not create commodities and exchange value, while claiming that peer production has the potential to create secondary market value. The logic of the market is however quite clear: the pursuit of profit. Without the drive for profit, no company can survive in the market. Companies cannot make a profit without exchange value. Thus, commodities without exchange value cannot be distributed in the market. Bauwens' argument, therefore, seems contradictory, since there are no major differences between capitalism and peer production with respect to the accumulation of capital, particularly if peer production integrates the market economy.

CBPP can be considered part of participatory democracy given that ordinary people, highly skilled or not, can participate in the production process. Peer production can eliminate most barriers to production materials and tools for ordinary people.

> …[the] economic system is based on open access—based on widely accessible information and associated access to productive capital—distributed into the hands of an increased number of people. We believe that a highly distributed, increasingly participatory model of production is the core of a democratic society, where stability is established naturally by the balance of human activity with sustainable extraction of natural resources. This is the

[20] These activities include communication, collaboration, cooperation, sharing and so on.

> opposite of the current mainstream of centralized economies, which have a structurally built-in tendency towards overproduction. (P2Pfoundation.net, 2009).

The leadership of CBPP is, however, quite controversial in terms of participatory democracy. It is neither liberal nor deliberative democratic (see Bozdag and Hoven, 2015). Even though open source communities mostly emphasise consensus between contributors (Moore, 2011), in some cases not all members of the community are eligible to be involved in the decision-making process. Peer production can be seen as a democratic production process in terms of the opportunity of participatory production, because anyone can easily get involved and choose a task to contribute to. However, when conflicts or disagreements arise in the community, most contributors do not play an integral role in resolving them.

The common management model in CBPP is a meritocracy, which means producers "are given equal opportunity to succeed (or to fail) based on how good they are as coders" (Weber, 2004, p.180). The more contributions producers make to the projects, the more powers they have in the decision-making process (Fielding, 1999). In a meritocracy, developers can have the right to vote on a controversial. Each member (developer or volunteer) can get involved in the discussion and when the discussion reaches an impasse, voting can be used as a method to solve the problem. Generally speaking, only developers that stand in the centre of the community can vote, not all members.[21] Developers writing codes, patching bugs, and solving problems have a right to vote concerning solutions to problems. Voters must be approved by co-developers in the community. Not all members can be involved in the decision-making process, only high technical skills enjoy this privilege. However, the power of open source communities is not just based on code that is open. As I said before, the most important point about CBPP is that social relations between peers such as sharing, collaboration, and cooperation can serve developers' creative growth. The discussions on ideas, innovation, the management of the community, the future of peer production, and the development of eco-friendly technology can also be important CBPP activities (see Benkler, 2006; Bauwens, 2009). It is unclear whether volunteers contributing to these discussions are approved as voters by the core group. If not, this means that those who contribute these discussions are ignored in the community.

[21] For example, volunteers mostly cannot vote to solve the problem.

Bauwens (2009, p.123) states that "most communities seem to combine a core leadership whose forms of power do not correspond to the command-and-control paradigm but are nevertheless influential, and which are often termed "benevolent dictatorship".[22] Even though the structure of the internet is horizontal, CBPP communities are often run by a benevolent dictatorship. This represents an important obstacle to the creation of a more democratic and horizontal organisation, in which each peer can easily participate in decision-making over community rules and project production policies. I will now focus on FOSS.

FOSS is one of the most successful examples of CBPP. The primary logic of FOSS production is to keep software code open. In this way, developers can have access to code to read, change, modify and share. The only condition developers must adhere to is that the modified software should be distributed in such a way that the modified code is kept open. The success of FOSS is based on software code that users usually find to be more reliable and functional, while being more rapidly innovative than software produced by most proprietary corporations with their conventional rigid management structures that impede innovation (see Raymond, 2001). FOSS can also be a business model in which developers make money from open source products. Open source does not invalidate profit, capitalism and intellectual property rights. Open source companies and supporters produce intellectual goods and make a profit out of them (Weber, 2004).

Steven Weber (2004, p.16) claims that "property in open source is configured fundamentally around the right to distribute, not the right to exclude". As I argued before, the digital commons is based on abundance, not scarcity. Abundance is not about the production of digital commons, it is about the copying and distribution of software, which is easy and cheap on the internet. Production of FOSS requires time, energy and the intellectual effort of creative people, all of which are limited resources. The increase of computing power can further restrict the availability of creative people, given that the demand for them rises. Weber (2004, p. 151) adds that "meaning and value depend on human mind space and the commitment of time and energy by very smart people to a creative enterprise". Value is created by intellectual labour, including the creative activities of many people. Software production can require a considerable amount of intellectual labour, but in comparison copying and the distribution of software might not

[22] Benevolent dictatorship refers to "the leader of a project and the person who alone has all the power to make decisions" (Ingo, 2006). I will give more details about the detrimental effects of benevolent dictatorship on peers in open source communities in Chapter 4.

be as labour-, time- and energy-intensive. Software does not require material manufacturing, and it is relatively easy to change and to share. The internet can enable users to share immaterial goods on social network platforms at a low cost. The software industry, therefore, has become one of the most effective fields for CBPP. Through the internet, FOSS can organise a great number of people to develop and to distribute open source projects. Thus, owning property in open source entails to the right to distribute it. Without the right to distribute, open source projects cannot be developed. Code is open to everyone, because open source production requires contributions of users and developers. The more distributed an open source project is on the internet, the more attention it gets. This is vital for the production of open source projects.

In some cases, firms and individuals can change the open license terms of software to restrict its distribution and make money from a commercial version of it. They usually use a dual license: GPL or another open license, and a commercial license. Products can be released under both licenses, but the products released under the commercial license might have extra functions that are not included in the GPL version. The Swedish company MySQL AB, used a dual license for commercial purposes. Another such example was Security Shell (SSH), a set of tools that encrypt data sent to and from servers and computers, and once an open source project. In 1995, the leader of the project, Tatu Ylonen, quietly changed the term of the license and restricted the commercial distribution of SSH. Ylonen also formed a company, the holder of the SSH trademark, to sell a version of the software to commercial users. The supporters of open source perceived the restriction of the SSH distribution as a betrayal. This is because Ylonen did not allow them to make money from SSH, a project produced by many volunteers, even though he used the product for commercial purposes (Weber, 2004). Production of SSH was still open source, but the distribution of the software was restricted by license and trademark. Besides code, the good reputation of the project was forged by open source communities. The restriction on use of the project's name by trademark rights, provided the leader and company owner Ylonen with an unfair advantage from which he made money. This is another example of hyper-exploitation of the volunteers' productive fun labour. The products copyrighted and trademarked are the creation of the open source community, rather than a sole beneficiary, just one person or his company.

As I have explained, FOSS consists not only of volunteers but also paid developers. Firms can provide funds for FOSS communities to support the production of open source projects. These funds are mostly used to cover the wages of core-developers.

In this way, core-developers might become full-time employees of the projects, rather than hobbyists contributing in their free or leisure time. Well-known multinational IBM was funding various FOSS projects at the beginning of the 2000s. IBM financially supported the Apache project , as it used the project in its hardware products.[23] Through the Apache license, IBM modified the Apache code and released it under an IBM brand, but the company had to state that the IBM version was based on the Apache code (Weber, 2004; Fienberg, 1999).[24] IBM as a proprietary company developed a new business model compatible with open source projects. In this model, the company did not buy proprietary software for its hardware products, but invested money to open source communities for the development of open source projects. IBM made a significant profit from this business model (Benkler, 2006). The main source of this profit derived from the exploitation of productive fun labour of volunteers. Kostakis and Bauwens claim that:

> …the firm [IBM] would spend about $100 million per year on general Linux development. So if the Linux community produces use value of $1 billion (if it were to be produced by paid labor), and even half of that is useful to IBM, then the firm gains $500 million of software development for an investment of $100 million… IBM would pay $2 to ten employees but would get a value of more than $20 by many more than ten contributors, from whom a considerable number would participate on a voluntary basis (Kostakis and Bauwens, 2014, p. 24).

IBM created a business model based on FOSS. Voluntary labour played a key role in the reducing of employees' wages and increasing the profit margin of the corporation. Kostakis and Bauwens adds,

> In this model, there is a continued creation of use value in the public sphere and, thus, an accumulation or a circulation of the Commons based on open input, participatory processes of production and Commons-oriented output. However, the accumulation of capital still continues through the form of labor and capital in the entrepreneurial coalitions. It becomes obvious that an increasing amount of voluntary labor is extracted in this process (Ibid, 25).

Open source products also acquire exchange value in the marketplace, as IBM sells hardware products that work with FOSS. The company does not directly sell open source software, but computer hardware loaded with open source software. FOSS, which is massively reliant on productive fun labour, can create value in the market and this value

[23] The Apache project "is a collaborative software development effort aimed at creating and maintaining a robust, secure, efficient, extensible, and open source implementation of an HTTP (Web) server" (Fienberg, 1999, p.42).

[24] The Apache license can be accepted a commercial license that is used for open source projects. Lawrence Rosen states that "the Apache license only requires an acknowledgment in "end-user documentation" or "in the software itself," not in "all advertising materials" (Rosen, 2014, p.91-92).

can be transformed into capital appropriated by the IBM. this demonstrates that hyper-exploitation can easily occur in FOSS communities.

Another good example of this was the purchase of GitHub, the most popular platform for open source software sharing, for $ 7.5 billion by Microsoft, one of the biggest proprietary software companies in the world, in June 2018 (Mackie, 2018). In October of that year, Microsoft also announced that it had joined the open source patent group Open Invention Network (OIN), and the company opened a library of 60,000 patents to the members of OIN. This case was a significant turning point in the history of the free open source movement – as well as for Microsoft –since the company directors had always openly opposed free open source principles. For example, in 1976, Bill Gates, the founder and then CEO of Microsoft, claimed in an open letter that sharing software was an "act of theft" (Gates, 1976). Former Microsoft CEO Steve Ballmer denounced GNU/Linux, the best-known free open source operating system, as "cancer" in 2001 (Greene, 2001; Mackie, 2018). Again, in 2005, Gates branded free open source supporters "new modern-day sort of communists" (Brown, 2005; Gates, quoted in Dean, 2005). However, in the post-Gates and post-Ballmer era, wherein the political economy of the software industry has dramatically changed, it appears that Microsoft has benefited from productive fun labour to make great profits through the operation and use of the free open source movement.

The relationship between proprietary companies and open source communities is controversial. Even though the finance provided by the corporations plays a key role in the payment of core developers' wages, volunteers are not paid. According to research, "paid contributors are spending more than two working days a week and volunteer contributors are spending more than a day a week on F/OSS projects" (Lakhani and Wolf, 2005, p.10). Even though volunteers spend less time on open source projects than paid developers, the number of volunteers is bigger than paid developers in open source communities (Ibid, p.9). Furthermore, volunteers and paid developers' contributions are creative. "More than 61 percent of our survey respondents said that their participation in the focal F/OSS project was their most creative experience or was equally as creative as their most creative experience" (Ibid, p.11). Creativity and productive fun labour are the backbones of open source projects, and firms can make profits from creative contributions that are not paid for. Even though the firms to some extent can contribute open source projects, and users mostly use those projects for free, most users do not make money from those open source projects; in contrast to but the firms who can make a significant profit

from the creative contributions of volunteers. This attests to a potentially unhealthy relationship between firms and open source communities. Karim Lakhani and Robert Wolf state that:

> The contribution of firms to the creation of a public good raises questions about incentives to innovate and share innovations with potential competitors. In addition, the interaction between paid and volunteer participants within a project raises questions about the boundaries of the firm and appropriate collaboration policies (Lakhani and Wolf, 2005, p.19).

The problematic relationship between firms and open source communities derives from the tension between the logic of the market and that of the commons (Berry, 2008). The commons created by the productive fun labour of volunteers can be converted to capital in favour of capitalists, showing how they benefit from open source products. Peer production, as this example underlines, does not only create use value, but also exchange value in the market. As stated above, surplus value of productive fun labour can give rise to the emergence of hyper-exploitation in open source communities, even though FOSS provides individuals with the possibility of freeing themselves from proprietary companies that produce closed source software (Rifkin, 2014). Proprietary products prevent users from changing and sharing. Closed source policies aim at a technological production model, where innovation serves the interests of capitalists, not those society. Innovation, therefore, is slow and profit-oriented under the IPR regime, but FOSS is a software production model aiming at fast, quality and cheap innovation. FOSS succeeds in its goals by virtue of a large number of volunteers giving up a significant amount of their productive fun labour. However, given the relationship between FOSS communities and the firms, FOSS can become a profit-oriented business model. In some cases, companies making use of open source projects might abandon open source policies with the aim of further profit making. The story of MakerBot, I will explain it in Chapter 5, is one of the most striking examples of companies that abandon open source policies to increase profits. Using a dual license or trademark on FOSS underlines the contradiction between open source policies and the logic of the market; it appears that this contradiction cannot be easily overcome.

Frederick Brooks (1995) claims that in a proprietary software company the work is divided, with the technical director giving a specific task to a paid developer. Creativity can be damaged by the command that restricts the autonomy of developers. “Skilled programmers were anything but replaceable components of an automated software factory” (Ensmenger, 2010). Proprietary companies believe that choosing the right

project and the right mentor can increase the productive ratio (Mockus, 2009). In a proprietary company, a division of labour is clear, and producers come under pressure from managerial hierarchies. However, in open source communities, volunteers can freely choose a task that they wish to work on. The attitude of contributors towards open source projects is a voluntary, fun involving free time activity. Choosing the task, therefore, is another important characteristic of open source production. It is time to discuss the main characteristics of FOSHW.

The Main Characteristics of Free Open Source Hardware

FOSHW is a relatively new field of peer production. Open hardware is quite an interesting idea as electronic hardware products consist of both intangible and tangible goods. As stated before, software is an immaterial product and copying and distribution of code are easy and cheap on the internet, but it is impossible to copy and share tangible goods at low cost easily. The concept of scarcity and abundance should be reconsidered for FOSHW in terms of copying and distribution of hardware products. FOSHW means hardware whose design is shared with peers in open source communities to be re-developed. Peers also share knowledge and information about the components of hardware and how designs are assembled (Oshwa.org, 2017). Hod Lipson and Melba Kurman claim that:

> Open source hardware is a growing movement in the personal fabrication community. If an inventor chooses to open source her hardware design, she makes publicly available all the schematics, detailed description of needed parts and software, drawings and “board” files – basically all the information anybody would need to identically re-create the product or object (Lipson and Kurman, 2010).

However, open source hardware also contains manufacturing hardware goods. Manufacturing open hardware is the most challenging aspect of FOSHW projects, because the production, recopying and distribution of open source design is quite similar to that of open source software. The concept of free hardware design is also used by Stallman to define peer production in the hardware field. He highlights “design” as he believes that free hardware can just cover the design of the hardware. He explains:

> Applying the same concept directly to hardware, free hardware means hardware that users are free to use and to copy and redistribute with or without changes. However, there are no copiers for hardware, aside from keys, DNA, and plastic objects' exterior shapes. Most hardware is made by fabrication from some sort of design. The design comes before the hardware. Thus, the concept we really need is that of a free hardware design. That's simple: it

> means a design that permits users to use the design (i.e., fabricate hardware from it) and to copy and redistribute it, with or without changes. The design must provide the same four freedoms that define free software (Stallman, 2019).

Free hardware or open source hardware emerged in the late 1990s along with the launch of Open Hardware Certification Program in 1997 by Bruce Perens. Open Design Circuits announced the Open Hardware Specification Project (OHSpec) in 1998. Dr. Samir Nayfeh established the Open Design Foundation (ODF) in 1999 (Oshwa.org, 2013). However, free hardware or open source hardware projects were developed in the mid-2000s, and these were: Arduino (2003), SparkFun (2003), Adafruit (2005), RepRap (2005) and OpenCores (2007). In 2009, the Open Hardware Design Alliance (OHANDA) was created by a group of participants at the Grounding Open Source Hardware summit to launch a service to certify open source hardware design. Because of this, OHANDA created a label, used as a trademark, to adapt the four freedoms of free software to hardware. These freedoms were: “the freedom to use the device for any purpose, the freedom to study how the device works and change it, redistribute the device and design, the freedom to improve the device and design” (Ohanda.org, 2009). The concept of freedom in hardware refers to the freedom to modify or share design and devices. Stallman explains the meaning of freedom for hardware thus:

> For hardware, this confusion tends to go in the other direction; hardware costs money to produce, so commercially made hardware won't be gratis (unless it is a loss-leader or a tie-in), but that does not prevent its design from being free/libre. Things you make in your own 3D printer can be quite cheap to make, but not exactly gratis since the raw materials will typically cost something. In ethical terms, the freedom issue trumps the price issue totally, since a device that denies freedom to its users is worth less than nothing (Stallman, 2019).

The distribution of design might be accessible on the internet, but the distribution of devices requires much more time and effort for peers. The freedom to share devices with peers is central for the community-based production model. The contributors to the community can create a support network where people share devices with their friends. Sharing tangible goods is a new phenomenon for the free open source movement. Around the world, hackers are looking for new ways to support people who wish to share devices with friends.

In spite of Stallman's aforementioned statement “not free beer, free speech”, the meaning of “free” here could also be free of charge.[25] Many FOSS products can be found on the internet free of charge; it is possible to keep some designs of hardware products cheap or cost free, but the manufacture of hardware products is certainly in need of raw materials. Therefore, the term “free” in regard to hardware projects can lead to confusion. Richard Stallman (2019) calls “Free Hardware Design” the projects produced by free open source communities. Moreover, “Open Source Hardware” (OSHW) (Ohanda.org, 2009; Powel, 2012), “The Libre Hardware” (Pearce, 2017) and “Desktop Manufacturing” (Kostakis et al, 2015) are usually used as titles for the hardware projects based on CBPP, but free open source hardware (FOSHW) (Pearce, 2012) is the common title of the hardware movement in my research.

There are a number of differences between FOSS and FOSHW in terms of their characteristics, including spatial, temporal, social, economic and evolutive aspects (Malinen et al., 2011). FOSHW requires a physical space to manufacture hardware goods. Online communities are still used to produce design and software. Design and software are produced globally, while hardware goods are manufactured locally (Kostakis et al., 2015). People can manufacture hardware goods at home, but they might need a physical space for the manufacturing of hardware. The physical space for collaborative production is called a hackerspace, a new type of physical place where hackers can come together and work on prototyping hardware designs. Hackerspace also offers hackers certain production tools in the manufacturing of hardware (Sleigh, 2013). It is a useful place for collaboration between hackers who want to adapt peer production for hardware manufacturing, but hackerspaces mostly cover their expenses, which include rent money, utility bills, costs of tools and so on, with membership fees (Prodoehl, 2011). Creating hackerspaces can be more difficult and costly than creating online communities based on email lists or digital forums. Access to a hackerspace, therefore, is not as easy as accessing online open source communities.

Hackers generally require more experience and skills in FOSHW than in FOSS. Producing open design hardware compatible with open source software is more difficult than developing solely open source software, as hardware goods involve developing software, designing hardware, and prototyping and manufacturing designs. Hardware hacking, from design to manufacturing, is a longer and more complex process than

[25] Stallman asserts that “free software” is a matter of liberty, not price. To understand the concept of free software, you should think of “free” as in “free speech,” not as in “free beer” (Stallman, 2004).

development of software. (for more details see Malinen et al., 2011). Hackers having greater skills and experience in the development of both design and software are required in the production of open source hardware products. Prototyping of open source hardware designs is another important part of FOSHW. Engineering skills can play a key role in the assembling of machines and electronic goods.

Furthermore, the development of open source software is more rapid than that of open hardware, because the prototyping or manufacturing of hardware requires more raw materials and energy. The number of FOSS developers is greater than the number of FOSHW developers, as there are problems of physical space, time and money in open hardware. It also includes production of design and code as well as prototyping design (see Malinen et al., 2011). Hacking software is also cheaper than hacking hardware. The mass manufacture of open hardware requires a considerable amount of capital investment. FOSHW communities, therefore, often need to develop a close relationship with capitalists to manage the manufacture of hardware products. Open source 3D printers provide people with new opportunities to manufacture plastic goods at home. Open source 3D scanners or laser cutters become new types of portable and cheap production tools for hackers, enabling them to manufacture hardware. 3D printers are used by scientists to develop equipment. Ana Maria Sedletchi (2019) asserts, “3D printing has resulted in the democratization of digital manufacturing. It’s not just having access to the theory; it’s having access to the same equipment researchers use to run their experiments”. Again, democratization refers to accessing research equipment cheaply and easily. Accessing research equipment is as important as access to theory, for scientists. However, these portable production tools are still in progress and FOSHW projects generally require more complicated production tools, more expensive raw materials, and more energy than FOSS projects (see Malinen et al., 2011).

Another problem is that the quality of FOSHW projects do not have a standard. The quality of copies of open hardware products depends on the quality of raw materials, the skills of producers, and the quality of production tools (Malinen et al., 2011; Bradford, 2014). Software, on the other hand, can be perfectly copied and distributed at low cost. Furthermore, the distribution of FOSHW goods is also costly. Hackers in open source communities for the most part do not have sufficient capital investment to manufacture their open hardware design (see Bolton, 2014). Capitalists, therefore, can be important players in the manufacture of FOSHW projects. Design and software of production are mainly managed by online communities, wherein hackers give up their productive fun

labour. Investors can benefit from open source software and hardware design to manufacture FOSHW projects. Volunteer labour in open hardware communities can turn into capital in favour of investors, who do not play an active role in the production of design and software. Thus, hyper-exploitation of productive fun labour can also become a significant issue in FOSHW communities. Hence, with FOSHW, not only software, but also design and documentation of hardware goods can be used by manufacturers to make a profit. Consequently, capitalists benefiting from open hardware projects do not see the need to spend so much money on R&D anymore.

FOSHW makes use of GPL, CC or other open licenses to protect design and software, yet copyright only covers artistic works such as books, paintings, designs and software. Inventors usually apply a patent for knowledge used for functional works. FOSHW projects consist of both artistic and functional works. However, FOSHW communities do not in the main apply for a patent on hardware goods of their own creation, because the application for a patent is time-consuming and expensive (Weinberg, 2014). But companies making money from open source hardware usually use their trademark to differentiate their own products from clones. Cloning, essentially, refers to the freedom to use, modify and distribute FOSHW design. Hackers can benefit from open source design and software to clone electronic hardware goods. However, a level quality of all open hardware clones is not guaranteed. Copying electronic hardware products can cause a problem in the market, as low-quality clones can damage the reputation of the respective open hardware projects. Companies selling open source hardware products can use a trademark to protect their reputation in the market. However, as I will discuss in Chapter 6 in more detail, the issue of who holds the Arduino trademark would cause a significant conflict in the leadership group of the Arduino community, and the community split into two distinct groups. I have explained briefly the main characteristics of FOSHW in this chapter, but I will explore the rise of FOSHW in more detail in Chapter 4. FOSHW is the main subject of this thesis. The issue of capitalist exploitation in open hardware communities will be widely discussed in the following chapters. For example, I will look at the RepRap project in Chapter 5 and Arduino project in Chapter 6 as empirical cases of FOSHW.

In this chapter, I have discussed the meaning of “hyper-exploitation”. The line between work time and free time becomes difficult to discern. The capitalist system not only exploits the labour of waged workers, but also the productive fun labour of hackers. Capitalists may not pay wages to volunteers who give up their time, energy, and labour

to open source communities. Capitalism brings a new dimension to the concept of exploitation in social production. Hyper-exploitation refers to capitalist exploitation, where productive fun labour creates surplus value which is turned into capital and hackers are not paid in return for this labour. CBPP becomes a collaborative production model where many people can easily participate in the production process. In this model, users have access to digital goods to use, study, modify and share. As stated previously, FOSS is one of the most successful examples of peer production developing a great range of open source software. FOSS can offer people a software production model that is faster, cheaper and more collaborative than the proprietary production model. On the other hand, it can provide capitalists with an opportunity to exploit productive fun labour in open source communities. Companies use FOSS products for their commercial purposes. Open source communities mostly support the collaborative relationship with technology companies to acquire funds, which are mostly used to pay wages of core-developers. IBM makes a great profit from the use of FOSS in their hardware products (see Benkler, 2006).

FOSHW is a hardware production model based on CBPP, in which communities produce software and design for electronic hardware goods. It has certain characteristics that differentiate it from FOSS. Hacking hardware requires a physical space to prototype and manufacture hardware design. Hackers need to have greater skills to hack hardware than software, because hardware designs must be compatible with software and manufacturing. Hardware manufacturing is not based on abundance. It requires a considerable amount of raw materials, energy and time in the production and distribution of hardware products. Portable production tools, such as 3D printers, scanners and laser cutters, enable people to manufacture hardware at home. However, in some cases manufacturing electronic hardware requires advanced production tools and sufficient capital investment. FOSHW, therefore, provides capitalists with a great opportunity to be involved in open hardware manufacturing. As I said before, productive fun labour plays a major role in the production of software and design for open source hardware, and manufacturers benefit from this. Capitalist exploitation in FOSHW communities is a significant issue that remains to be analysed. I will discuss this issue in the following chapters. Now, I will explain the methodology of the thesis in Chapter 3.

Chapter 3: Research Methodology and Ethics

In this chapter, I outline the research methods appropriate to my research questions, particularly interviews, thematic analysis and corpus analysis. I then explore the research ethics related to my project. At the start of the chapter, I explain the methods used in this research. I collected data from RepRap and Arduino developers' mailing lists and conducted interviews with hackers on the mailing lists. I elaborate on the types of interviews I had during the data gathering process and explain why I chose these different types. I also give details on the background of the interviewees. Then I explain thematic analysis and how I have employed thematic analysis in Chapters 5 and 6. I discuss how corpus text analysis helps me normalise data on the mailing lists and how I use the data in thematic analysis. At the end of the chapter, I explain the ethical review of this research. For now, I focus on research methods I applied for the thesis.

Research Methods

In this first section, I provide a brief overview of the methodologies that have informed my work and that I have selected in order to elicit answers to the questions that drive this research. The method is important in my research as it guides the way in which I have undertaken the research, bringing forward some aspects of the research domain I am interested in and by necessity backgrounding others.

Whenever one selects a methodology, it is important to recognise the extent to which this creates a particular perspective on a research question, which has to be taken account of reflexively in the research. In order to try to balance out this methodological effect, I have sought to use a number of different approaches in my method. This is important for a number of reasons: (1) it allows a multi-perspective approach to my research questions, enabling a triangulation of perspectives which deepen my understanding of the problem domain; (2) one of the problems with researching digital communities, such as the FOSHW movement, is that there is simultaneously too much information – usually from mailing lists, amongst others – and not enough data – usually as a result of the reluctance of informants to provide interviews, or when they do, giving short or limited answers to the questions; and (3) this methodological approach has also allowed me to cross-fertilize my research as findings from one method (for example, the concordance and content analysis of the mailing lists have been used to provide a

conceptual input into the thematic analysis of the interview data to help develop topics, concepts and categories for my work).

My aim has been to build a framework for understanding the FOSHW movement, informed, as it is, by this wider analysis of the thematic of collected data and interviews. To further understand the FOSHW movement, I have, therefore, looked at discussions on the mailing list regarding the roadmap of the projects and communities. In this way, I have also discussed capitalist exploitation in FOSHW communities with the help of thematic analysis and corpus analysis. Qualitative data have been collected online and interviews.

1-Mailing Lists Archives

FOSHW is a production model based on online communities where developers and designers come together and become part of the production, distribution and consumption processes of hardware projects. Although FOSHW communities organise offline events like summits, conferences or create hackerspace to come together physically, online activities are the primary communication strategy between hackers, typified by forums, mailing lists, chat groups, and so on (see Coleman, 2013; Kelty, 2008). It is claimed that the free open source movement is based on a new kind of production model, the so-called commons-based peer production (CBPP) model (Benkler, 2006). This model has been very successful in parts of the software industry, and increasingly, in the hardware sector. The research looks at how the CBPP model is applied to hardware products, tensions between the free open source movement and capitalism, and the issue of capitalist exploitation in FOSHW communities.

I collected qualitative data on RepRap and Arduino mailing lists and websites by scraping these pages into a textual archive. In some cases, individuals create online communities where communication or connection is made in a digital way and this was a useful resource for this project. It is argued that without face-to-face communication, people can interact with others on the internet; further, internet users can set up digital platforms for themselves to play an active role in the production, distribution, and consumption of digital goods (Castells, 2013). As a researcher, my main concern in understanding FOSHW is to analyse online communities where FOSHW goods are produced by hackers, so these sites are very useful. In particular, the conversations among developers on the internet have provided rich detail of the tensions between hackers.

Producers do not feel they need a physical workplace where they physically come together and communicate face-to-face with their peers; instead, people can be organised in online communities to manage the production, distribution, and consumption of digital goods. Distribution of information or knowledge in online communities is easier than in offline communities. The most important thing, I think, is that all data on the internet is automatically archived, and this data offers the researchers great opportunities to conduct the empirical research, which is an effective method to analyse the issue of capitalist exploitation, free time and creativity in FOSHW communities. In this thesis, I collected qualitative data from RepRap and Arduino mailing lists and websites, which were publicly available.

2-Interviews

My second approach to the collection of primary data was through interviews. My social network analysis helped me to narrow my choice of interviewees using the mailing list archive of the projects.[26] The most active developers in the social network analysis were ranked for me to conduct interviews, as part of the process of primary data collection, since these developers spent much more time on the mailing lists, and acquired great knowledge of what goes on in the communities. I sent an e-mail post in the form of a letter, in which I briefly introduced myself and explained my research project to the RepRap and Arduino hackers, from the most active to the least active, inviting them to be interviewees in my research.

A number of developers replied to my email communication within a week. Some of them agreed to be interviewees for my PhD project, but others refused to be part of the interviewing process. I kindly thanked those who did not accept my request, not e-mailing them again. However, most developers did not reply to my first e-mail, and I sent them a reminder two weeks later. After the second post, some additional developers contacted me to become interviewees in my research. However, most developers did not reply to my second mail. I did not send a third e-mail to those who did not respond to my first two mails. I initially contacted 82 developers, members of RepRap (37) and Arduino (45) developers' mailing list, and 29 of them agreed to contribute to my data collection interviews.

[26] I used the result of social network analysis to decide who would be interviewees for my research. The result of social network analysis did not play a key role in the analysis of communities. Therefore, I did not explain it broadly in the thesis.

The hackers who gave me positive responses were given more details about my thesis, and I discussed with them the interview methods and they were informed of the ethical research guidelines that I use in the research. Three interview techniques were used during the data collection process: mailing interview, online video interview, and face-to-face interview. As both RepRap and Arduino mailing lists consisted of international hacker groups, some hackers suggested to me that the best interview style for them was an email interview because English was not their first language, and that they could write better than speak in English. A few developers whose native language was English also wanted to do a mailing interview due to feeling uncomfortable on a video chat medium or lack of proper time for an interview. The hackers I tried to interview were mostly busy with a current hardware project; it was almost impossible to find an appropriate time to arrange a meeting for interview on a video chat program. Therefore, I used the mailing interview technique for 12 developers (7 for RepRap, 5 for Arduino) of both communities. I interviewed 11 developers (6 for RepRap, 5 for Arduino) on a video chat tool and one developer in a face-to-face interview (one Arduino) in both communities.

Altogether, I carried out 24 interviews with the members of mailing lists of RepRap and Arduino. Although 29 developers accepted to be interviewees, contact with 5 developers was not possible for various reasons (see below). The interviewees had a wide range of education levels, age groups, and nationalities. However, I was only able to arrange interviews with a few female developers in both mailing lists – this was mostly due to the heavily skewing towards the male gender in these technical communities, as has been documented elsewhere (see Reagle, 2013). The full version tables showing the demographic backgrounds of the interviewees are in the appendix (see Appendix 2), but here is a short summary.

Name	Age	Gender	Education	Country
ReRM03, 04, 05, 06, 09, 10, 26, 33, 41, 61	43-52-39-65-55-70-45-42-61-64-41	All Male	High School Bachelor Master PhD	Serbia, Germany, Portugal, UK, USA' New Zealand, Sweden

Table 3.1: The Backgrounds of RepRap Interviewees (Summarized version).

Name	Age	Gender	Education	Country
ArdM03, 04, 06, 07, 10, 20, 30, 33, 34, 37, 51, 61, 72	32-50-48-36-56-41-45-24-39-44-38-55-26	One Women Other is Male	High School Bachelor Master PhD	Netherlands, Germany, Denmark, UK, USA' Spain, Sweden

Table 3.2: The Backgrounds of Arduino Interviewees (Summarized version).

Qualitative interviewing has been used in this research rather than survey interviewing, because my research seeks primarily to explore capitalist exploitation in FOSHW communities where hackers play a key role in the production of open hardware goods by providing their creativity and free time. Interviewees can play a more active role in qualitative interviewing, instead of passive respondents who answer questions in unoriginal ways (Holstein and Gubrium, 1995, p.8).

Semi-structured interviews were conducted in this research. I chose to apply thematic analysis, appropriate for such interviews, I prepared a list of questions (see Appendix 3), including seven open-ended questions, a consent form, and a participation information sheet. The consent form and the participation form were sent to the interviewees before doing the interviews, and I requested that the interviewees return the signed consent form after the interviews. The interviews lasted mostly 30-40 minutes. I will briefly describe the contents of the interview questions.

The first question was about the demographic backgrounds of the interviewees, and how hackers got involved in open source communities. This question provided me with valuable data to see to what extent RepRap and Arduino communities were diverse. Hackers' accounts of told of how they became involved in open source communities, how long they had been involved, and how they could move from software hacking to hardware hacking. Almost all hackers had initially been involved in a FOSS community.

The second question concerned the ways in which hackers used open hardware goods in daily life. The third question looked at the motivations of hackers contributing to open hardware. The answers to the third question provided me with important data to explain the reasons why hackers gave their creativity and free time to open source communities mostly for free. The fourth question asked how hackers contacted each other, and how they contributed to a FOSHW project. The fifth question concerned

intellectual property rights. I wanted to learn what hackers thought about copyright, copyleft, patent and trademark because most legal protection tools are used as a bridge to transfer creative activities into profits or income. The sixth question was about making money from FOSHW projects. The resulting data told me whether hackers made a living from open hardware (or not). The second part of the question focused on hackers' thoughts on the collaborative relationship between businesses and open source communities. The last question related to the future of FOSHW. The main point here was whether – and how- hackers saw the future benefits and potential risks of open hardware to society.

The RepRap and Arduino platforms are primarily based in online communities. Therefore, people all over the world can join these communities if they have an internet connection and are interested in the RepRap and Arduino projects. Consequently, the participants in my research, were drawn from a wide range of countries. It would have been impossible to carry out face-to-face interviews with all developers because of the prohibitive cost of travel to the many countries. And needless to say, this would have been a time-consuming process. Online video chat tools provided me with a useful opportunity to conduct interviews on the internet. I used Skype, Ring, and Jitsi for the interviews. Before the interviews, I only knew Skype as a video chat platform, but some developers rejected Skype during the interviews because it was not a FOSS product and they did not use proprietary software; so, I downloaded and installed Ring and Jitsi, both FOSS, to my laptop. The interview on the video chat platforms was conducted as a conversation between the interviewer and the interviewee. I usually asked sub-questions during the interviews, apart from the seven main questions, to understand the technical terms or jargon in the field of FOSHW. Online video interviews were conducted in my place of residence.

Although video chatting platforms provided significant opportunities for the interviews in terms of time and money, the platforms also posed some challenges. As previously mentioned, RepRap and Arduino are international online communities where developers hail from different parts of the world. Each time I tried to arrange a meeting on an online video chat platform, I used local time in the UK as a reference. For this reason, I missed a couple of meetings and had difficulty in convincing the interviewees to rearrange a meeting.

Moreover, some technical issues, mostly stemming from poor internet connection, disrupted the conversations with the interviewees. In some cases, I was forced to ask the

same questions again and again because of faulty internet connection or a technical issue with the communication tools. Two different recorders were used during the interviews in case one stopped recording. By the end of the interview process, I had 11 different recorded audio documents, rich primary source material for my empirical cases.

I conducted just a single face-to-face interview during the data collection process. The interview was carried out in the office of the interviewee. Again, I used two different recorders. Before the interview, I had chatted with the participant regarding my research and my educational background. The interview was carried out in the form of a conversation. The face-to-face interview took a little more time than that of a video interview.

Transcribing the interviews was probably the most challenging and time-consuming part of the video and face-to-face interviewing. I transcribed 11 different audio records, each between 30 and 40 minutes, within about two months. Nvivo, which is a textual analysis tool, was used for the transcription. The transcription process took much longer than expected for several reasons. Firstly, the hackers used terms which I was not familiar with. Secondly, some developers were not native speakers; at some points, different accents or pronunciations made it difficult to understand what the interviewee said. Thirdly, I am not a native English speaker. Therefore, after finishing the audio transcriptions, I sent both transcriptions and recordings to an English native speaker for double-checking. The data collection process, including the mailing lists and the interviews, took place between June 2016 and July 2017.

Due to the refusal of a limited number of interviewees to give video interviews, I resorted to e-mail. Mail interviewing consisted of three stages, with the questions sent in parts. As soon as the interviewees responded to the first tranche of questions, I posted the second and then the third tranche. However, two interviewees did not return the second or third parts; they failed to reply to the e-mails sent by me, and I lost contact with them. This was one of the weaknesses of the email interview process. However, I used the data gathered from the participants who only replied to the first or second sections of research questions. In addition, those interviewees who refused to give face-to-face or online video interviews did not provide as much rich detail as the participants who did. Although the transcriptions of the face-to-face and online video interviews took considerable time, the data collected from face-to-face interviews was actually much richer and more detailed than that of email interviews. However, some of the hackers who preferred mail interview were highly active members of the RepRap and Arduino developer mailing lists. Even

though most of them gave short answers, certain parts of their responses provided valuable data for the research.

3-Thematic Analysis

The data from the mailing list archives and interview transcripts were subjected to thematic analysis given the nature of the data method applied was qualitative analysis. Victoria Clarke and Virginia Braun state that:

> Thematic analysis (TA) is a method for identifying, analyzing, and interpreting patterns of meaning ('themes') within qualitative data. TA is unusual in the canon of qualitative analytic approaches, because it offers a method – a tool or technique, unbounded by theoretical commitments – rather than a methodology (a theoretically informed, and confined, framework for research). This does not mean that TA is atheoretical, or, as is often assumed, realist, or essentialist. Rather, TA can be applied across a range of theoretical frameworks and indeed research paradigms (Clarke and Braun, 2017).

The theoretical framework of my thesis is broadly Marxist, drawing on the work of contemporary Marxists to address of exploitation in the field of digital production (Fuchs, 2014a; 2014b; Hardt and Negri, 2017; Harvey, 2017). There is no problem in the application of thematic analysis alongside Marxist theory, as TA can be applied across a range of frameworks. It is a research method that can be employed to identify and analyse thematic patterns. I have explored capitalist exploitation of hackers' free time and creativity in FOSHW communities. A theoretical thematic analysis was used in this research. This sort of thematic analysis "tends to provide less a rich description of the data overall, and more a detailed analysis of some aspect of the data" (Braun and Clarke, 2006, p.84). In this analysis, research questions were initially developed, and themes and concepts were identified to help answer the research questions. My research questions were not developed through the data collection. Also, I supplemented this with semi-structural interviews including seven open questions, which were compatible with the theoretical framework of my thesis.

Thematic analysis toolkits were invaluable in my analysis of the mailing list and interview data. The analysis includes "the searching across a data set / be that a number of interviews or focus groups, or a range of texts / to find repeated patterns of meaning" (Braun and Clarke, 2006, p.86). Identifying themes in the analysis was important because "the process of data analysis involves constant comparison of the differences and similarities in the data, in order to come up with themes and patterns" (Nglube, 2015, p.142).

Mailing lists archives contained a significant amount of data. It was impossible to read and re-read all the data, in order to identify similarities and differences on the mailing lists for the purposes of coding of the data. When I carried out the data coding and identified themes, I applied corpus analysis to normalise and classify the mailing list data, but the themes I identified were not related to the most frequent concepts on the mailing lists. Corpus analysis I was applied to the mailing lists' overall content. It was important to select themes that highlighted similarities and differences in mailing list discussions and were also relevant to the research questions. In this thesis, as my work addressed the relatively new phenomenon of FOSHW, I was particularly interested in the main issues raised by hackers in their discussions.

In this research, I did not carry out an economic survey of companies linked to open source communities because they have not been disposed to share information and knowledge with researchers about their revenue. I contacted certain companies for interviews and to obtain information about the open source business, but they did not reply to my e-mails. I did not have access to a primary source or document that showed me how an open source business made a profit, and how the companies shared this money with open source communities. I did not do an analysis of the flows of computer code or hardware design within the communities. Prototyping or manufacturing FOSHW requires raw materials and physical space. The discussions about the manufacturing side of hardware hacking were crucial, because simply analysing the flows of computer code and design would not yield the necessary data to help identify the economic tension between open source companies and manufacturers. Also, it would be unfeasible to complete an economic analysis of the companies or an analysis of the flows of code and design within the scope of a 3-year PhD programme.

I did the data coding process of the interviews manually because the volume of transcriptions was reasonable and manageable. I read and re-read all the data, and I highlighted the data on PDF files in different colours. I realised that certain themes were recurring and that there were similarities and differences over these themes. In the interview transcriptions, I identified new themes that did not exist on the mailing lists. The issues of Arduino clones, and of license and sharing in the Arduino community were identified. Furthermore, I applied the corpus analysis and analysed the transcriptions of RepRap and Arduino communities separately. Each community could discuss different themes because each community had specific issues and concerns. For example, cloning was a hot topic in the Arduino community, but in the RepRap community, almost no one

mentioned it. Fun was an important theme in the RepRap interviews and on the RepRap mailing lists whereas there was little data on fun in the Arduino community. Consequently, I classified the different themes for each community.

I followed the steps developed by Braun and Clarke (2006, p.87-93) in the thematic analysis: "1- familiarizing yourself with your data, 2- generating initial codes 3- searching for themes, 4- reviewing themes, 5- defining and naming themes, 6- producing the report". I undertook the corpus analysis to normalise online data to see key concepts on the mailing lists. I read and re-read the transcriptions. I also conducted a coding process by highlighting key concepts and discussions around these concepts. I collated the data relevant to each code. I identified, and then checked themes if they worked. I drew up a thematic map of the analysis with potential themes. I generated clear definitions and names for each theme. At the end of the analysing process, I wrote a report that enabled me to conduct a final analysis of themes, and to test coherency of thematic analysis, research questions and literature review.

I analysed the key themes in the mailing lists and interviews. It is important to note that even though both RepRap and Arduino are part of the FOSHW movement, the discussions in the RepRap mailing list were richer and more diverse than those of Arduino for the purposes of thematic analysis. There were important discussions on the RepRap mailing list regarding the economic and cultural side of the FOSHW movement. The interview data from the RepRap mailing list was central to Chapter 4, which focuses on the RepRap community. The Arduino mailing list included conversations on mostly technical issues and technological improvements. This mailing list was not a suitable platform on which developers could discuss cultural or ideological questions in the movement. The interview data proved very useful for Chapter 5, which treats the Arduino community as an empirical case. Nvivo, a software tool that facilitates good qualitative analysis, was also used for thematic analysis when evaluating the interview data. The interview data were categorised on Nvivo, rendering the process of analysis much more manageable.

4- Empirical Cases

Before I explain why these communities were chosen as empirical cases, I will briefly define empirical research and empirical case to emphasise and highlight its scope and features. Empirical research means "originating in or based on observation or

experience… researchers should be guided by direct observations and experiences about phenomena, without prejudice to, or even consideration of, existing theories" (MacKenzie, 2013). An empirical case "provides data on what is going on, emphasises features of a new condition/phenomenon, or describes the current status of existing condition/phenomenon" (Betterthesis.dk, 2020).

The empirical study inquiry enabled me to manage multiple sources of evidence and to develop a triangulation of perspectives that facilitates the understanding of free open source hardware. I have applied multiple empirical cases so that I could investigate FOSHW as a contemporary phenomenon and within a real world context. For empirical research of the FOSHW movement, I chose two FOSHW communities as empirical cases to gain the primary data and to make the research process much more manageable. The FOSHW movement contained tens of online communities currently working on hardware devices (see Sjoberg, 2016). With a PhD thesis on limited time, it proved impossible to look at all the FOSHW communities presently active. Empirical cases helped me at this point because "Qualitative empirical studies can provide rich, deep contextual data to help us understand a phenomenon" (Betterthesis.dk, 2020). For this reason, I picked up on two FOSHW communities: RepRap (3D printer) and Arduino (microcontroller boards).

The RepRap community, which produces a self-replicating manufacturing machine, was one of the earliest FOSHW projects, and home to the most popular 3D printer in the hacker movement (see Moilanen and Vaden, 2013). RepRap also allowed hackers to create new 3D printer projects which can be released under a different brand or name. For instance, Ultimate, MakerBot and Prusa 3D printers were initially developed in the RepRap community, which was influenced by the hacker movement. For this reason, RepRap merited being one of the empirical cases of the FOSHW movement. The other example case was of the Arduino community, which produces small computer boards that enable users to build electronic devices. Arduino became one of the most popular microcontrollers among hackers since it is a user-friendly device (Qureshi, 2015). Both empirical cases were well-known projects within the FOSHW movement and had serious potential to lead desktop manufacturing. However, the most important reason why I chose these communities as empirical cases was that there were hundreds of developers that gave up their creativity and free time to both communities. RepRap and Arduino mailing lists had many active developers involved in discussions on the mailing lists. Both mailing lists provided rich data for analysis. Other FOSHW communities did not offer the wealth of data as did the RepRap and Arduino communities.

I focused on two empirical cases in order to discuss the hyper-exploitation of volunteers' creativity and free time. In addition, the ideological struggle between the developers on the mailing lists was analysed.[27] The primary data of the empirical cases were collected from developers' mailing list archives and the interviews. 24 semi-structured interviews were conducted with RepRap and Arduino contributors, focusing on motivations, expectations of the developers, communication types in the community and the thoughts of developers regarding intellectual property rights. These data were supplemented by readings and analysis of the communities' websites and developers' mailing list archives.

Both RepRap and Arduino communities have considerable data on their mailing lists. In the lists, hackers communicate with one another, discussing problems and solutions, and sharing experience and documents. In short, mailing lists are the leading platforms of the communities for hackers to become part of the production process. The amount of data from both RepRap and Arduino mailing lists was tremendous, yielding about 40,000 pages in Word. Following the data normalisation and cleaning process, I applied social network analysis and corpus text analysis, broadly detailed in the next paragraphs. Using the result of the social network analysis, I decided who would be interviewees on the mailing lists. I observed the tensions and discussions in the community and applied thematic analysis to the mailing list and interview data in order to analyse the production, distribution, and consumption of FOSHW products, the structure of the community, and the ideological struggle among the hackers. Now, I will explain in more detail how I conducted the corpus text analysis.

5- Corpus Text Analysis

In order to carry out word frequency analysis, I imported the cleaned mailing list archive into Nvivo, from which I obtained a word cloud picture and a word frequency list. However, the NVivo word list did not show the "keyness" of words on the mailing lists or in other terms "the frequency of a word in the text when compared with its frequency in a reference corpus" (Froehlich, 2015). Keyness enables us to see which terms are used unusually often in a particular corpus and therefore may be key terms in relation to its content. Therefore, I applied a corpus analysis, meaning "a form of text analysis which

[27] The ideological struggle in this context refers to a state where hackers having different political ideas are in conflict with each other regarding the aims of the movement.

allows you to make comparisons between textual objects at a large scale (so-called 'distant reading'). It allows us to see things that we don't necessarily see when reading as humans" (Ibid). Corpus text analysis is a quantitative method which enables the researcher to obtain particular statistical results. I used this method in my research because I tried to find keywords on the mailing list archives. Corpus analysis is a technique helping deal with large amounts of raw data, in order to identify important themes for analysis.

I chose AntConc, a textual analysis tool, for the corpus analysis. I imported the cleaned mailing list document into AntConc, and also uploaded a stop list to eliminate some common words that are meaningless for my research such as "am, is, are, I, you, they" and so on. The British National Corpus (BNC) word list, which consists of more than a million words, was uploaded into AntConc as a reference corpus to measure the keyness of keywords on the mailing lists. For the stemming process, I also uploaded a "lemma list" into AntConc to reduce different word forms (design, designs, designing) to their common lemma (design).[28] [29] The corpus analysis list was limited to the 50 most popular words, which included mostly nouns and verbs (see Appendix 1). Most of these words were specific terms used in the production of FOSHW projects, but there were also words used in daily life.

For the RepRap mailing list, the most frequent words, including works, prints, making and needs, constituted the key vocabulary used in the production process of FOSHW projects. Furthermore, these words were integral to the technical discourse of hackers. The developers usually explained how the software and machines worked, how they were built, printed or used, and how they were made, developed or controlled on the mailing list. Some words such as sell, buy, commercial, market or cost, were more usually linked to the commercialisation of RepRap projects. The members of the mailing list often used a range of vocabulary: help, need, support, suggest, idea, and so on when collaborating. Collaboration among peers was vital to free open source production. For legal protection of RepRap projects, patent or license was often discussed by developers. The other most common words were features or components of RepRap projects, for

[28] Stemming means "the process of reducing inflected (or sometimes derived) words to their word stem, base or root form, generally a written word form." (Vanderbush, 2017).

[29] Lemma refers to "a form of a word that appears as an entry in a dictionary and is used to represent all the other possible forms. For example, the lemma "build" represents "builds", "building", "built", etc." (Cambridge.org, 2019).

example, machine, software, firmware, technology, innovation, and documentation. Furthermore, the RepRap mailing list archive and the interviews conducted with the developers included rich data regarding political or ideological tensions between the hackers of the FOSHW movement. The concepts of open source, self-replicating, customisation, license, patent, and fun were identified as key themes for analysis. The discussions around these concepts provided me with a great opportunity to apply a thematic analysis in which I also put the concepts discussed in Chapter 1 and 2 such as capitalist exploitation, creativity, productive fun labour, hyper-exploitation and so on. I will give more details about the key concepts and thematic analysis of the RepRap community in Chapter 5.

The Arduino developers' mailing list contained quite technical details and discussions regarding the development of software and designs of Arduino projects. Concepts such as library, software, code, hardware, and files were core elements of the production process of open source hardware. Hackers shared the files including code and designs with each other on the mailing list. Files were saved in a library.[30] Some other words, namely using, needs, building and making, were used in the documentation to explain how to develop the projects. Collaborations between developers were the most important production activity. Consequently, the concepts of help and support were frequently used on the mailing list. Technical discourse was dominant, and political or ideological discussions were hardly ever held on the Arduino developers' mailing list, since the community had an agreement that included the terms of service decided by Arduino company. The developers joining the Arduino community had to obey the terms of the agreement, whereas the RepRap developers' mailing list contained serious political and ideological debates over the community roadmap. RepRap had no agreement governing the terms of service, as decided by a company or group of people. Therefore, for thematic analysis, the key concepts were selected from data in the interviews conducted with Arduino developers. The themes were open source, license, sharing and clones. I analysed these themes with the concepts I introduced in Chapter 1 and 2. I will expand on this in Chapter 5.

The methodology I used in my research was somewhat sophisticated. It consisted primarily of a qualitative method, but part of the methodology also included quantitative

[30] A library also can mean a specific form of shared code.

methods, such as corpus text analysis, mainly based on a counting process. However, the primary research methods were interviews and thematic analysis.

As I stated previously, FOSHW is a community-based production model in which hackers collectively produce open hardware products. Individuals on the one hand develop their creativity in peer production and choose a task to develop their skills. Collaborative communication plays an important role in the emergence of co-creativity. On the other hand, the communities share an organisational model in which individuals may not participate in the decision-making process. This type of dilemma, between individual and collective action, is common in open source communities. Individuals become involved in FOSHW communities in the name of collaboration, cooperation and having fun, yet collective action can force individuals to perform tasks unwillingly. Horkheimer and Adorno (2002, p.16) claim that "what is done to all by the few always takes the form of the subduing of individuals by the many: the oppression of society always bears the features of oppression by a collective". Individuals voluntarily contribute to FOSHW projects. They can, therefore, stop contributing to projects if they are not happy, but most communities still have rules that members are required to obey. The tension between individual action and collective action derives from capitalist exploitation because individuals' labour in collective production serves the accumulation of capital. Horkheimer and Adorno (2002, p.xvii) state that "the individual is entirely nullified in face of the economic powers". In the culture industry, individuals do enjoy strong autonomy in the production process, but hackers have individual autonomy within communities. However, the capitalist system exploits the creativity of individuals in social production, which becomes a new object of hyper-exploitation (Kostakis and Bauwens, 2014), as producers are not paid for their creative activities.

Even though peer production is a production model based on "decentralized decision-making in commons based peer production as indicative of a distributed power relationship in which participants have high levels of individual autonomy" (Meng and Wu, 2013, p.134), the management of peer production is mostly based on meritocracy, in which a benevolent dictatorship claims the right to decide on open source projects and community (Raymond, 2001; Berdou, 2010). It is important to note that there is a tension between individual autonomy and the governance model of peer production. Conflicts are unavoidable in communities. Individual agendas are common, giving rise to conflicts between contributors, or between volunteers and leaders (Kittur and Kraut, 2010). In this thesis, I also focus on an analysis of the decision-making processes in communities.

Research Ethics

Because this thesis involved research methods that included human subjects, it was reviewed by the Social Sciences & Arts Research Ethics Committee. The result of the ethical review application was that my study posed a low risk of harm to the participants. The last application of ethical review was approved on May 28, 2017.

RepRap and Arduino developers' mailing lists were public. This enabled anyone who wished to join the mailing list to become a member without having to ask permission or have restrictions placed on them. Both mailing lists were freely accessible for anyone with an internet connection. Furthermore, RepRap and Arduino were free open source communities where hackers and users shared or exchanged knowledge. Supporting "free flow of knowledge" is an important part of hacker ethics and culture. The data on the mailing lists were used in my thesis to study FOSHW communities in depth. From this research, I aimed to make theoretical contributions to the ongoing discussions regarding the free open source movement. Accordingly, my use of data from the RepRap and Arduino mailing list archives did not raise ethical questions, even though I did not obtain the consent of all mailing list developers whose data was used. It was impossible to access all people on a RepRap mailing list numbering 303 contributors, and the Arduino mailing list with its 462 developers. "Freedom to study", a claim developed by the free software movement (see Stallman, 2002), was accepted as an essential principle in the free open source movement, to encourage users and developers to share and use knowledge and experience in the communities. As a researcher, I collected and used these data for my PhD project, and the findings of the project will also be shared with other researchers and members of the free open source movement interested in the social and cultural background of the movement.

However, the identities of the developers on the mailing lists were anonymised with certain numbers, in the following form: Ard+number or RepR+number. The number was assigned to contributors as a type of pseudonym, calculated from their position in the social network analysis. This ranked the developers on the list according to their level of activity, from the most to the least active. The mailing list data were used in the thematic or corpus text analysis linked to the anonymised developers.

Although all interviewees were sent consent forms, in which they were asked to sign and return the forms to me, I received just one signed consent form. I sent two

separate e-mails to remind them to send me the signed consent form, but no one replied to my messages. They verbally accepted to be a participant in my research, but I could not get a written consent form. This probably represented the most important ethical dilemma in my research. The participants I interviewed online (Video and mail interviews) did not send me signed consent forms, so I changed tack to obtain interviewees' consent. I decided to send an e-mail which included a consent form to the participants, in order to obtain their consent. As a result, I received the interviewees' approval to use the data gathered from the interviews in my research. I asked all interviewees "Please could you confirm if you are happy that I use our interview in my research?" and every interviewee I emailed gave me positive feedback. This was how I handled this ethical issue.

Private data pertaining to the developers on the mailing lists was not used in the thesis, and I did not email the developers for any reason other than requesting the interviews. The developers' e-mail addresses were not shared with the third parties. At completion of the social network analysis, developers' e-mails were removed from the list showing contributors' positions based on their activity level.

All data gathered from the interviewees have been stored on my computer and my portable drive which have been encrypted. Both devices have been kept locked. I have used a flash drive to back up the data in the event that the computer was broken or stolen. I have not shared the data, which has included interviews, with any third parties. The interviewees in the research were selected from the developers on the mailing lists. Their identities have been anonymised. The quotations from the interviews have been referenced with the expression "interview with an anonymised name" while the quotations from the mailing lists have been referenced with the expression "an anonymised name from the mailing list".

In the next chapter, I look at the critical background to the term "hacking", and the FOSHW movement.

Chapter 4: The Emergence of Hacking and the Free Open Source Hardware

This chapter seeks to understand the background of the hacking culture and the free open source hardware (FOSHW) movement. As noted in the first chapter, hacker culture relies on the commons-based peer production (CBPP) model, including a range of peers' activities based on a new work ethic involving "collaboration, cooperation, and sharing" (Himanen, 2001; Rifkin, 2014). In this chapter, the role of hackers in the digital transformation will also be discussed, together with the practices of the FOSHW movement. I will focus on the opportunities and limitations of the movement. Hardware hacking aims to create both hardware and software products.

FOSHW is a relatively new movement, at least newer than FOSS, and will be the main subject of this research. The opportunities and challenges of FOSHW will be discussed before the fifth chapter, which analyses the RepRap project as an empirical case. Before I start discussing the concept of hacking and hackers, I would like to briefly explain how standardisation is promoted by capitalism and proprietary companies, and how hacking activities are different from the firms-based production.

In the capitalist system, firms are described as bureaucratic, mechanistic, rationalistic systems (Moore and Karatzogianni, 2009). Phoebe Moore (2011, p.87) adds "market-based capitalism is based on the private ownership of the means of production and hierarchically organised corporations". As I discussed before, proprietary companies have top-down management organisation, in which workers or employees lack the autonomy to play an active role in the decision-making process of production. Managers decide duties for employees in the proprietary company. The employees do what the managers say. Under the management of proprietary companies, standardisation is unavoidable; the management model is based on a one-to-many communication structure that prevents employees from developing collaborative communication enabling individual creativity. The employees here are isolated individuals who cannot take control of the production process because, in proprietary companies, the owners of the companies have the private ownership of the means of production. Moore (2011, p.89) asserts that "workers' knowledge within capitalist companies automatically becomes the intellectual property of employers". The workplace is under the discipline of the company owners. In contemporary capitalism,

> 'control' has become an increasing dilemma in the context of studies of the workplace. 'Control by machine' was proposed with the development of information technology and service-sector occupations, but ideas for workplace discipline have since expanded. Skills, knowledge and innovation have become competitive markers for employability (Moore and Taylor, 2009, p.111).

Control of knowledge and information is a significant matter in proprietary companies, firms, and factories, as knowledge (or information) is a valuable economic product, not just as a commodity to sell, but also an essential element of production. In the production process, workers must possess sufficient knowledge and information to safeguard their jobs. Moore and Taylor (ibid) add that "in order to remain employable in a knowledge economy, workers need to adapt to an entirely new set of codes involved in the production, mediation and application of knowledge". Employees are controlled by capitalists in companies and factories. The "campus" work environment can be a new sort of controlled space where employees are isolated from society. It appears that the campus makes a workplace more enjoyable for employees. Moore and Taylor add that:

> the presentation of work as more of an intellectual game than as traditional economic production is reinforced by such practices as Microsoft's 'campus' work environment, in which the hacker-slacker generation moves seamlessly from college to workplace with scarcely a noticeable change in the carefully constructed informality of their surroundings (Ibid, p.103).

Microsoft's campus is a workplace controlled by Microsoft Corporation. Hackers or creative persons usually work for the company as a contracted employee. The creativity of employees can be appropriated by the company. In this way, the company might keep creative minds inside the campus. In the Amazon campus, the company's exercises stricter control of its employees than Microsoft.

> Its swelling campus is transforming a swath of this city, a 10-million-square-foot bet that tens of thousands of new workers will be able to sell everything to everyone everywhere... Tens of millions of Americans know Amazon as customers, but life inside its corporate offices is largely a mystery. Secrecy is required; even low-level employees sign a lengthy confidentiality agreement. The company authorized only a handful of senior managers to talk to reporters for this article… (Kantor and Streitfeld, 2015).

In Amazon, employees compete, and fail to develop collaborative relationships. Under contemporary capitalism, corporations can force their employees to work hard. Amazon "is conducting an experiment in how far it can push white-collar workers to get them to achieve its ever-expanding ambitions" (Ibid). As I said before, employees have limited autonomy in a firm's production process, and tend to be controlled by their managers.

The top-down managerial system allows managers to normalise and standardise social relations in firms, companies, or factories.

Although proprietary companies, firms and factories can control the distribution of knowledge and digital goods through intellectual property rights, CBPP is also a part of a knowledge-based economy. However, as I said before, property in open source is the right to distribute rather than the right to exclude. IPR can be used as a legal tool allowing peers to freely use, re-copy and distribute immaterial goods in open source communities. Peers have the autonomy to choose a task for peer production, and such production is not based on standardisation, or controlled by managers. Hackers benefit from peer production to develop open source projects, as hacking is a creative activity requiring collaborative communication and participatory production.

Hacking and Hackers

In this section, I look at the struggle between the intellectual property rights regime and the hacker (Berry, 2008, p.27; Lewis and Leys, 2010). This emerged in the 1970s and 80s in the software industry (Stallman, 2002). Developers working for university labs in the 1970s were willing to access finished software code to understand the way it worked and to redevelop it. Yet they refused to share software code with non-members of the lab, due to lab policy of keeping all source code regarding software systems closed. Software code was also strictly protected by copyright law (Stallman, 2002). The struggle for the distribution of software code led to conflict between hackers and software corporations.

The struggle in the software industry has helped drive the development of the internet. Castells (2013, p.57) claims that "the new field of communication in our time is emerging through a process of multidimensional change shaped by conflicts rooted in the contradictory structure of interests and values that constitute society". The on-going struggle around software code is a vital parameter in the analysis of power relations in the digital field. Accessing software code means also accessing property in the software industry. Software products mostly consist of intellectual labour and do not need too much energy or raw material to distribute. A software developer can easily produce software products at home by means of their PC and electricity. Production conditions in the software industry are radically different from production conditions in the nineteenth century when workers did not have the means to make complex products at home. Indeed,

hackers have created models whereby people might fulfil their needs at home. Before focusing on FOSHW, I look at the terms “hacking” and “hacker”.

Hacking means “exploring the limits of what is possible, in a spirit of playful cleverness. Activities that display playful cleverness have ‘hack value’” (Stallman, 2002, p.17). Tim Jordan (2008, p.5) also states that “the hack is the way hackers touch the infinite, the way they imbue their actions with spiritual meaning and (or) change the world”. The hack is a material practice that produces differences in the digital field. The practices usually include operating technology and developing new software or hardware products for new effects (Ibid). Developers performing hack practices are called “hackers”; the hacker is also defined as “a person who uses computers to gain unauthorized access to data” (Oxforddictionaries.com, 2017). This definition more accurately refers to the concept of “cracker”. Eric Raymond explains the difference between crackers and hackers: “Hackers build things, crackers break them” (Raymond, 2001, p.196). The term hacker also refers to “an enthusiast, an artist, a tinkerer, a problem solver, an expert” (Ibid, p.xii). Richard Stallman describes a hacker as “someone who loves the program and enjoys being clever about it” (Stallman, 2002, p.17). However, Jordan (2008) sees cracking as part of hacking. Crackers and free open source programming can be considered as the two core components of hacking.

Hackers are talented and skilled creators of alternative platforms serving the free flow of information. Jordan (2008, p.16) claims that hackers are twenty-first century warriors leading the digital transformation in society through their contributions to information technology and digital culture. In this respect, hackers push the boundaries of the digital era. Hackers have been active players in the creation of internet users' rights, with hacking activities that support open access, transparency, sharing, peer production and so on.

Lawrence Lessig (2002, p.11) asserts that “our generation has a philosopher. He is not an artist or a professional writer. He is a programmer”. Programmers have played a key role both in the construction of the internet and the production of digital items, and some of them, in parallel with the digital transformation, have created a new work ethic and culture (Himanen, 2001). The term hacker has a strong connection to computer technology and the internet. Linus Torvalds, one of the best-known leaders of the GNU/Linux project, uses the terms “computer” and “internet” when defining the notion of “hacker”.

> A "hacker" is a person who has gone past using his computer for survival ("I bring home the bread by the programming") to the next stages. He (or in theory but all too seldom in practice, she) uses the computer for his social ties - e-mail and the Net are great ways to have a community. But for the hacker, a computer is also entertainment (Torvalds, 2001, p.xvii).

There are certain key elements in the motivation of hackers: "survival, social ties, and entertainment" (Torvalds, 2001, p.xiv), "playfulness, pranking, cleverness, source code, humour" (Coleman, 2013, p.17). The term hacking has a strong relationship with the concepts of play, fun and enjoyment. Berdou (2010, p.25) states "FL/OSS developers continue to be driven primarily by the desire to learn or the enjoyment derived from solving problems, or by the prospect of a (better) paid job". Having fun is among the foremost motivations of open source contributors. There is a significant relationship between fun and play. David Graeber (2014) adds: "having fun, doing something we do well for the sheer pleasure of doing it. Engaging in a form of play". As stated previously, Play here does not refer to leisurely game playing. It is not like playing video game with friends. It is much more playing chess. It is a collaborative and competitive[31] process to solve a problem or overcome a challenge. Peter Kropotkin argues that

> many plays are, so to speak, a school for the proper behaviour of the young in mature life, there are others, which, apart from their utilitarian purposes, are, together with dancing and singing, mere manifestations of an excess of forces—"the joy of life," and a desire to communicate in some way or another with other individuals of the same or of other species—in short, a manifestation of sociability proper, which is a distinctive feature of all the animal world (Kropotkin, 2012, p.50).

Playfulness is a process of human socialisation, and a process of learning through activity. In open source communities, communities of practice, hacking itself can be seen as a form of play through which hackers develop technological products collaboratively. It is difficult to draw a line between work and play here. Kucklich (2005) states that:

> The precarious status of modding as a form of unpaid labour is veiled by the perception of modding as a leisure activity or simply as an extension of play. This draws attention to the fact that in the entertainment industries, the relationship between work and play is changing, leading, as it were, to a hybrid form of "playbour" (Kucklich, 2005).

Computer game modification is termed "modding" in the gaming community. For example, Counter-Strike is a modification of Half-Life. Counter-Strike was later sold as a distinct product for PC and Xbox. Modding, in this way, prolongs the shelf-life of products and leads to an innovation model, in which the industry seemingly can avoid

[31] The competitive process here is not destructive, but constructive.

taking commercial risks. Modders can acquire celebrity status in the gaming community and this prestige helps them to find a job in the game industry, as in the case of Minn Le, the creator of Counter-Strike; yet most players do not benefit from the games in this way. Players' unpaid labour of is seen to be the same as indulging a leisure pursuit. The line between work and play becomes indistinct and playbour occurs as a hybrid form. The creativity of modders provides developers with ideas to develop new games that become successful in the market and reduce the costs of marketing research and development (Kucklich, 2005). It is important to note that modding in this context refers to a sort of hacking practice.

Hacking in open source communities does not resemble work in proprietary companies. Hacking is more fun, more enjoyable, and playful than the production of closed source technology. This feature of hacking therefore can garner a lot of attention and support. A significant number of developers and volunteers can contribute to free open source projects without expectation of payment. The proprietary company is seldom supported by volunteers. It is difficult for the proprietary company to compete with hackers' communities in terms of more rapid innovation and cheaper products (Raymond, 2001). Fun and playfulness increase the number of volunteers in communities. Voluntary labour in open source communities helps speed innovation and create cheaper products. Without the playfulness aspect of peer production, open source communities may struggle to obtain voluntary labour. Kucklich, therefore, calls voluntary labour play labour or playbour. But I call it productive fun labour because hackers explain their contribution to a community in terms of fun. In hacking practice, the line between fun and labour is unclear. As I said before, the term fun refers to voluntary production in this research. Having fun means entertainment in the process of hacking practice or open hardware, in other words productive leisure time. It does not mean playing cards. It is important to note that the term play can be used for both productive leisure such as playing chess and unproductive leisure such as playing a computer game. Playing in hacking practice means solving a problem in a clever way, rather than a repetitive action in a game where the rules are already set. Therefore, the term play labour can be confusing for hacking activities. Linus Torvalds explains the meaning of entertainment for hackers:

> I mean by entertainment more than just playing games on your Nintendo. It's chess. It's painting. It's the mental gymnastics involved in trying to explain the universe. Einstein wasn't motivated by survival when he was thinking about physics. Nor was it probably very social. It was entertainment to him.

> Entertainment is something intrinsically interesting and challenging. (Torvalds, 2001, p. xv).

Hacking also can means changing the rules of a game, not simply following those rules (Stallman, 2002). Hackers, for example, have not followed the rules of the intellectual property rights regime, and they have led the emergence of FOSS through a new production model based on playfulness, collaboration, and fun. Proprietary companies do not, in the main provide their employees with such a working environment. The companies, therefore, have changed their policies regarding hacking communities in recent years.

Capitalism is now developing a new way to profit from open source products, as the system cannot prevent the global spread of the free open source production model. Even though corporations have in the past tried to criminalize open source activities as piracy or illegal acts, free open source communities have expanded, and capitalists have now stopped accusing open source supporters of criminality. As aforementioned the Microsoft leaders were extremely hostile to FOSS until the 2010s, then the company purchased the GitHub platform in 2017. Clearly, Microsoft has changed its stance towards FOSS.

Hackers are generally members of an online community where they can contact each other and share their code and ideas. However, the meaning of hacking and hacker has changed over the years. This research is especially interested in hackers who programme or design FOSHW projects and is not concerned with hacktivism, cyberwar or cybercrime. Now, I will give a brief history of hacking to show how its meaning has evolved over almost three decades.

The Brief History of Hacking

The history of hacking can be divided into four 1-) computerization and network technologies; 2-) the crackers' golden age; 3-) redivision and the resurgence of free software hacking; 4- dedifferentiation of hacking (Jordan, 2017). The first stage of hacking emerged on the internet as cyberspace where a range of techniques was applied to manipulate materialised information; online communities were created, and programming as a profession grew, with the growth of the “programming proletariat” and free software developers. Hacking took on a “do-it-yourself” attitude to manipulating information technologies (Ibid).

The second stage of hacking history contained “cracking” activities that involved entering other people's computers illegally through a series of techniques including exploiting technical faults, and social engineering. Hacking was a group activity rooted in political and intellectual motivations. The programming proletariat grew, as did the number of free software developers. Free software enabled the development of some important programmes such as Emacs, Apache and Linux. Following these breakthroughs within the free software communities, the meaning of hacking changed from cracking to the innovative political practices of free software based on networked production forms (peer production) and openness. Furthermore, with the dot.com boom, capitalists clearly saw the internet as a platform for the accumulation of capital. Hacking gained a new meaning with more and more people entering cyberspace, as the internet became a vital aspect of people's daily lives (Jordan, 2002; 2008; 2017; Stallman, 2002; Raymond, 2001; Coleman, 2013; Himanen, 2001; Kelty, 2008).

The third phase of hacking history involved the prominence of free software and emergence of open source software (OSS), as well as ethics of creativity, the rise of cybercrime and growth of hacktivism. OSS quickly emerged in the free software movement and developed into an open source-friendly business model in which programmers could much more easily make a living from OSS products. The OSS movement also developed a relationship with ICT companies. For example, IBM created a fund for open source communities in return for using OSS in its hardware products. Creativity and digital aesthetic were new elements in hacking. This phase also included cybercrime, such as dark web drug selling, online scams, spyware and malicious types of virus, and hacktivism, which means using the internet for political actions, such as mass distributed denial-of-service (DDoS) attacks. Wikileaks was the target of a DDoS attack on 28 November 2010 following its release of US diplomatic materials and leaking of secret information (whistleblowing).[32] Hacktivists aimed primarily at achieving political outcomes through their actions on the internet (Jordan, 2017; Jordan; 2008; Coleman, 2015; Benkler, 2006; Weber, 2004).

The last stage consists of two main trends: first, state-backed hacking, in other words, where hackers are backed by states to attack other states' facilities and networks in order to sabotage or damage them. Second, hardware hacking, which refers to manipulating software and hardware aspects of goods. This hacking grew in popularity

[32] Wikileaks is a multi-national media organisation that analyses and publishes large dataset of restricted or censored official documents involving corruption, war and spying (Wikileaks. org, 2015).

in parallel with the growth of 3D printers, laser cutters and scanners. These hacking activities also involved the creation of new offline spaces such as hackerspace, makerspace, or fablab, besides online platforms and communities. Hardware hackers are also known as makers (see Jordan, 2015; 2017; Anderson, 2012; Pearce, 2012). In this thesis, I focus on hardware hacking, which is the last stage of hacking history. Before I explore the rise of open source hardware, I discuss the hacker community and intellectual property rights in open source communities.

The Issue of Hacker Communities

The hacker movement consists of communities of practice that exist mainly online. Communities of practice means "groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly" (Wenger--Trayner and Wenger-Trayner, 2015). Open source is community-based production in which a group of individuals with a passion for doing or learning something collectively, develops software products. The hacker community is an online community "of like-minded people who jointly develop[ed] software" (Moritz et al., 2018, p.205). Hackers possess different levels of skill and experience in the community, yet these like-minded people contribute to the community with writing code, reporting a bug, distributing software, sharing ideas, feedback, co-development, brand recognition and so on (Moritz et al, 2018). As I said in Chapter 1, the FOSS community consists of two main groups: co-developers at the centre of the community and volunteers on the periphery (Berdou, 2010). The core-developers, who have greater skill and experience in writing code or developing a design, are more active in the production process than volunteers, who mostly contribute in their free time. Still, collaborative communication between co-developers and volunteers boosts creativity in open source communities. The communication process between members of the community is integral to the production process itself, in that CBPP is nothing without collaboration, cooperation and sharing practices on the network platform.

Accordingly, as stated in Chapter 1, the internet is not just a traditional mass communication tool based on a one-to-many communication process, but a platform that enables interactive and many-to-many communication. Hacker groups have created a global movement through the internet (see Castells, 2001; 2013). Network platforms have enabled hackers to build their organisations at the international level. The relationship

between the internet and the hacker, in this respect, is synergic; the history of the internet cannot be properly understood without the practices of the hacker.

Moreover, the hacker community has a new ethical background. The hacker ethic promotes access to computers; free flows of information; mistrust of authority; decentralisation; no discrimination by race, age or position; digital aesthetic, and changing your life for the better with computers (Levy, 2010, p.28-34).[33] Supporting the free flow of information, including keeping code open, is one of the fundamental rules of the hacker ethic. Hackers, therefore, build social spaces for the collective development of technology, such as internet chat relays, mailing lists, online forums, code repositories, hackerspace/makerspace, FOSS projects and hacker conferences (Coleman, 2017). Hackers pursue these activities with motivations derived from anti-authoritarian and hobbyist principles that do not obey the strong intellectual property regime and market rules.

Jordan (2008) asserts that free open source hacking consists of three components: community, object, and property. The community is a platform where many experts, developers and volunteers come together to work on a project. The motivations of community members comprise intellectual challenge, fun, and ideological commitment. Object refers to a product, a software programme, or a part of a software programme. Property in open source is a kind of community ownership of software products. Owners of FOSS allow users to make alterations and then make it freely available to others. Copyleft licensing, is a vital tool for FOSS developers to make their properties freely available to all. As previously stated, property in FOSS implies the right to distribute, not to exclude (Weber, 2004).

The hacker community, however, faces challenges in deciding the structure and decision-making process. Although the structure of the internet relies on horizontal networks of communication, the organisation of hacker communities is not quite horizontal. FOSS communities might support individual and collective actions in the production and distribution of software goods, but there is a tension within communities between collective and individual action. This tension is reduced through collective decision-making or consensus (Milan, 2015). However, it is hard to reach a consensus on all matters as communities often count thousands of members. Thus, communities are generally run by a leader or a group of people who decide on community policy. The

[33] Steven Levy missed “gender” as a category that should not be discriminated against in the hacker movement. I think gender as a category should be added to these groups.

"benevolent dictator" is described as "the leader of a project and the person who alone has all the power to make decisions" (Ingo, 2006). The benevolent dictator can share their responsibilities with co-developers who "own" the subsystem. The other members of the community are contributors or volunteers; they make up the largest group in the community, and most of the time are not involved in decision-making (Raymond, 2001).

It must be said that the mass participation of volunteers in the production process of FOSS projects has been a tremendous boost in the creation of a democratic network platform. One of the preconditions of a democratic system is to make the production process democratic (Fuchs, 2014a). In this sense, the mode of production used in the GNU/Linux project can be accepted as democratic, in terms of participation in the production process and access to code and information. However, the process of decision making in the GNU/Linux community is somewhat problematic, due to its top-down organisation and the benevolent dictatorship that rules the community. There are other types of management model for the free open source communities besides benevolent dictatorship. However, all communities consist of a leader and/or groups that hold different positions of authority. Informal rules and relations usually govern the communities. Even though there are certain democratic FOSS communities such as Debian, hierarchy based on meritocracy is the reality for most. The members who have more skills or make more contributions play a more central role in deciding community policy (see Coleman, 2013). Relations of power exist not only between the hacker communities and the corporations but also between the members of hacker communities.

> The process of formation and exercise of power relationships is decisively transformed in the new organizational and technological context derived from the rise of global digital networks of communication as the fundamental symbol-processing system of our time. Therefore, the analysis of power relationships requires an understanding of the specificity of the forms and processes of socialized communication, which in the network society means both the multimodal mass media and the interactive, horizontal networks of communication built around the Internet and wireless communication (Castells, 2013, p.4).

This underlines the existence of power relations in FOSS communities. A top-down management model does not fit with the notion of a democratic society when the decision-making process should be performed by all sections of that society.[34] Digital platforms,

[34] Christian Fuchs (2014a, p.14) claims that participatory democracy is "a society in which all decisions are made by those who are concerned by them and all organizations (workplaces, schools, cities, politics, etc.) are controlled by those who are affected by them. Such a society is not only a grassroots political

in theory, give citizens the possibility of setting up a more democratic culture, through decentralised networks, mass-to-mass and horizontal communication (Castells, 2013, Fuchs, 2008). However, Raymond argues that the structure of open source communities should be top-down.

> One of the things that seemed clearest was that the historical Unix strategy of bottom-up evangelism (relying on engineers to persuade their bosses by rational argument) had been a failure. This was naive and easily trumped by Microsoft. Instead of working bottom-up, we should be evangelizing top-down—making a direct effort to capture the CEO/CTO/CIO types (Raymond, 2001, 177).

The top-down model implies a hierarchical structure, as in corporations where owners and CEOs make the key policy decisions (Locsin, 2019). The cathedral model, criticised by Raymond for making the production process inefficient and slow (Raymond, 2001, p.31), effectively uses the top-down dynamic, leading to the concentration of power at the top. It is a little surprising that one of the leaders of the open source movement should argue that top-down is the most appropriate model for open source communities.

The concepts of cathedral and bazaar developed by Raymond define two different management and business models in the hacker community and in proprietary companies. The GNU/Linux development model was essentially based on peer production, in which many developers could contribute open source projects. Owners of open source software could sell their products to make a living.[35] Raymond (2001) claims that this model work much better than the proprietary type of production and free software, where a small number of experts produced software.[36] The bazaar model is a collaborative production model based on peer production while the cathedral model refers to a top-down production model where a small group direct the production process. Eric Raymond (ibid) explains the bazaar model thus:

> From nearly the beginning, it was rather casually hacked on by vast numbers of volunteers coordinating only through the Internet. Quality was maintained not by rigid standards or autocracy but by the naively simple strategy of releasing every week and getting feedback from hundreds of users within days, creating a sort of rapid Darwinian selection on the mutations introduced by developers. To the amazement of almost everyone, this worked quite well (Raymond, 2001, p.16).

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democracy, i.e., a society controlled by all people but also an economic democracy, in which producers control the production process and the means and outcomes of production".

[35] Raymond called it "bazaar".
[36] Raymond called it "cathedral".

Users in this context essentially mean the members of the quality control department of corporations. However, users are volunteers in the production and distribution of products, receiving no payment for these activities. Feedback from users is a crucial part of production but feedback does not have to be simply technical; it can have aesthetic, economic and social aspects. In general, interactions between peers are part of production; even just asking a question or sharing an article in the community can provide a new idea for software developers or other peers. However, those who do not make technical contributions are not usually accepted as contributors to projects (Raymond, 2001; Coleman, 2013).

As I mentioned before, IBM developed a new business strategy by staying out of the production of software products that contain "hardware & hardware maintenance costs, software license costs, support for software licenses, personnel costs, facilities costs" (Perco and Foster, 2016). Apparently, companies did not earn money by selling FOSS, but they could sell the hardware loaded with free open source products. Free open source developers can earn money from the funds provided by the companies. For example, Core Infrastructure Initiative (CII), a project of the Linux Foundation, is itself funded by donations from the tech giants IBM, Google, Amazon, Intel and Facebook. Hackers working for the Linux Foundation benefit from this funding (Oberhaus, 2019). However, capitalists can manipulate hackers into working on the projects that are profitable for their companies. In this way the top-down company poisons open source communities. Hackers do not pursue tasks of their choosing- that they might enjoy; instead, managers of proprietary companies assign them tasks. Hacking activities in this context are no longer playful or fun, having become duties. Hackers are effectively under the patronage of the companies (see Berdou, 2010).

As I will discuss in Chapter 6, the Arduino company has top-down management of FOSHW projects. The capitalist exploitation of creativity in the Arduino community has led to a company structure on the top-down model. Another example, seen in Chapter 5, is that of the MakerBot company, initially an open source 3D printing company, which then changed to a proprietary company that did not share code. Capitalists were able to pressure the leaders of the company by the power of their investment, and open source policies in MakerBot were abandoned. The design and code of MakerBot 3D printers became assets of proprietary companies. As discussed in Chapter 2, the appropriation of productive fun labour by the companies can be termed "hyper-exploitation" (Kostakis and Bauwens, 2014; Harvey, 2017). Production of Maker-Bot 3D printers was gradually

changed from a horizontal, peer-to-peer model to a top-down production model under the directorship of investors.

FOSS is a movement where many peers participate in the production of a project to develop their skills and reputation. Raymond (2001, p.84) asserts that the main motivation of hackers in the open source community is to gain this reputation. Hackers who make money from their skills rely primarily on their reputation to obtain job offers. They tend to see open source projects as platforms to invest their time and work on products and build their reputations. They are frequently unable to make money from the open source projects unless they are in the leader or co-developers' team, but still want to be part of the team to see their names in the list of contributors. As Aparici et al. state,

> …young people do not carry out their digital productions for commercial purposes, but for the mere pleasure of sharing information and knowledge with a community… The search for recognition is the main objective behind the creation of these media texts, which are donated to a community (2018, p.206).

In the games industry, gaining a good reputation can help modders make a living.[37] Kücklich (2005) states that "Counter-Strike's creator, Minh Le, enjoys a celebrity status that enables him to find employment in the games industry". However, I think it is important to note that the leader and co-developers in open source communities not only develop a reputation but also sometimes make money directly from these projects. Open source communities as practice of communities are important issues for FOSS and FOSHW since the structure of communities and relations between groups in the community can give us significant details on hardware hacking.

The Issue of Intellectual Property Rights (IPR)

Intellectual property rights are an important issue for hackers who keep code and design open for collaborative production, as on the one hand hackers can struggle with proprietary companies restricting the flows of code and designs, and on the other they have to protect their designs and software from those who could turn open source products into closed source ones. IPR therefore acquires importance for FOSS and FOSHW communities, to save their rights and sustain software and hardware hacking. IPR is usually used as a legal tool to restrict flows of creative intellectual works. It can also clear the path from hacker's creative works to their exploitation by companies. Hackers in

[37] Modders are those who modify a digital game.

FOSS communities have struggled with the rules of IPR to create online communities where knowledge and digital goods are freely distributed. FOSS communities have already succeeded in the production of software, developing skills, reducing costs of intangible digital goods, contributing to the creation of network platforms and developing the internet (Gupta et al., 2016). The success of communities has shown that people organised on the internet can be part of the production and distribution of digital goods without a significant amount of investment or a strongly hierarchical organisation (Weber, 2004; Wark, 2004; Kelty, 2008). The structure of the internet allows users to reproduce and distribute their digital goods at low cost (Benkler, 2006; Rifkin, 2014). Consequently, the production and distribution of digital products have been somewhat freed from the strictures of ICT corporations underpinning the "market dictatorship" (Lewis and Leys, 2010) and "intellectual property rights" (Berry, 2008). Braithwaite and Drahos assert that:

> Intellectual property rights are a source of authority and power over informational resources on which the many depend – information in the form of chemical formulae, the DNA in plants and animals, the algorithms that underpin digital technologies and the knowledge in books and electronic databases (Drahos and Braithwaite, 2002, p.12).

As stated in Chapter 1, intellectual property rights serve the interests of copyright holders rather than creators of information and digital goods. Drahos and Braithwaite (2002, p.15) add that "the bulk of intellectual property rights are not owned by their initial creators but by corporations that acquire intellectual property portfolios through a process of buying and selling, merger and acquisition". The holders of copyright or patent aim to restrict the flows of intangible goods with IPR. In contemporary capitalism, the commodification of knowledge serves the drive for profit even though knowledge was part of the intellectual commons in the past. Accordingly, IPR has become a tool enabling the transfer of intellectual commons to private hands (Drahos and Braithwaite, 2002). IPR offers technology companies monopoly privileges; whereby they direct innovation and technological development in their own interest rather than to the benefit of society (Ibid). The system of monopoly privileges is called the intellectual property right regime, and has come to mean that "a small number of US companies…captured the US trade-agenda-setting process and then, in partnership with European and Japanese multinationals, drafted intellectual property principles that became the blueprint for TRIPS" (Ibid, p. 12).[38]

[38] Trade Related Aspects of Intellectual Property Rights (TRIPS)

Production and distribution of goods are mostly based on standardisation, which "consists of building a society around a standard with an implied script that brings people and things together in a world already full of competing conventions and standards" (Timmermans and Epstein, 2010, p.84). Standardisation in intellectual property is linked to the commodification of knowledge and digital goods. Furthermore, the implementation of standards is top-down; a small number of copyright holders play determine standards in the field of intellectual property rights. Moreover, standardisation "in its popular uses is derogatory; it connotes a dull sameness, the suppression of individuality in the service of industrial uniformity" (Ibid, p.71). Although standards are required to form a society, standardisation under the IPR regime leads to the homogenisation of that society, erasing diversity.

Hacking inherently means producing differences (Jordan, 2008, p, 9). Therefore, standardisation and homogenisation are incompatible with hacking activities. The products of hackers' creative activity can be commodified under the IPR regime. The hacker community automatically produces differences, because doing something in a clever and different way is the fundamental premise of hacking. Conversely, goods become commodified and standardised when proprietary companies homogenise closed source products. There is a tension between non-standardised hacking activities and commodified proprietary products. Most striking is the tension between non-standardised hacking activities and commodified open source products because as previously explained, hackers coming under commercial pressure tend to the development of products that make money instead of choosing tasks they find challenging and interesting. This situation seriously undermines the hacking ecology. Given these clear imbalances, the relationship between open source communities and proprietary corporations is not mutually beneficial; indeed it can be detrimental to open source communities.

However, the hacker work ethic approves of code sharing, collaboration between peers, and copyleft or open licenses. Therefore, hackers who support strong intellectual property rights, and reject code or project design sharing, may not find a warm welcome in hacker communities. Developers can try to build a new strategy for collaboration between the market and hacker community if it does not go against the central tenets of hacker work ethics. However, a path to ease tensions between the commons and the market would seem hard to find. At least, it appears impossible in the near future because the tensions outlined above are integral to the current socio-economic system serving the interests of a few capitalists. In the 1990s, the internet was viewed by some users as a

critical tool to liberate society (Castells, 2001; Fenton, 2012). Yet today, scholars discuss the monopolisation of the internet by the Big Five Tech Companies of Apple, Microsoft, Facebook, Amazon, Google (Van Dijck et al., 2018; Mosco, 2017). The internet has been dominated by tech giants for years now, and pessimistic views have displaced the one time optimism regarding the future of the internet. The commercialisation of the internet has put freedom of users at risk through the harvesting of individuals' private data by tech giants (Fuchs, 2014a; 2014b).

The hacker work ethic emerged in an era when the intellectual property rights regime has been integral to the dominant global economic model, but there have been critical tensions between the regime and this ethic at certain points, over production, distribution, and consumption of software products (see Himanen et al., 2001). The policies of IPR were discussed and some principles were rejected by the developers advocating free software (Stallman, 2002).[39] This represented a breaking point in the development of hacker culture, which as we have seen had been primarily based on sharing practices and collaboration. These developers led the establishment of a hacker movement that developed alternative digital projects.

As said before, in 1976 Bill Gates released an “open letter to hobbyists” regarding the copying of software (Gates, 1976). The letter's principal target was open source principles, and it advocated instead the intellectual property rights regime. University labs did not allow developers to share software, code, and knowledge in the name of copyright policies. However, some software developers fell foul of copyright policies that restricted the flow of information, because the developers usually promoted their programming skills by checking the software code already written. By the mid-1980s, proprietary software companies and university labs following copyright policy were dominated by the software industry (Weber, 2004; Tozzi, 2017).

In 1985, the Free Software Foundation, a non-profit organisation, was founded by Richard Stallman, a charismatic leader of the free software movement. The foundation aimed to support the movement in its struggle for free software. For this movement, access to information/knowledge was seen as the fundamental precondition of freedom. In the wake of the popular FOSS movement, internet users started to raise their voices against the policies of ICT corporations that did not sufficiently take account of their privacy and freedom (Gnu.org, 2017). The movement raised users' awareness of the

[39] Richard Stallman was one of software developers who led the struggle for free software in the 1980s.

strong copyright policies restricting their freedom, bringing software products under control. Under the intellectual property rights regime, software products copyrighted by corporations were not free and open; for that reason, users could not see source code and could not make any changes to them. On the contrary, the products actually determined or controlled users' actions. Freedom in this context referred to freedom to run, freedom to study, freedom to redistribute, freedom to modify (Gnu.org, 2017).

The FOSS movement has put the intellectual property rights regime in a difficult position by eliminating scarcity in the software industry. The production and distribution of software projects cannot be strictly controlled by the owners of the corporations. Consequently, capitalism might face “a crisis of control” (Beniger, 1986), since the production and distribution of products are getting cheaper, and FOSS products are rapidly becoming cost free (Rifkin, 2014). Considering that capitalism is a political-economic system that uses the scarcity of raw material as a practical element in the balancing of supply and demand (see Beniger, 1986), it follows that the free flow of software on the internet must represent a significant obstacle to profitability for the tech giants.

The FOSS movement has been in conflict with the technology cartels for more than three decades. The movement perceived as a danger by the Microsoft company in the 2000s. As stated before, Microsoft CEO Steve Ballmer accused GNU/Linux, an open source kernel, of being “a cancer”. He also said that “Linux is not in the public domain. Linux is a cancer that attaches itself to an intellectual property sense, to everything it touches” (Ballmer, quoted in Greene, 2001). Also, Bill Gates, who is the co-founder of Microsoft, suggested that:

> There are fewer communists in the world today than there were. There is some new modern-day sort of communists who want to get rid of the incentive for musicians and moviemakers and software makers under various guises. They don't think that those incentives should exist (Gates, quoted in Dean, 2005).

Nonetheless, free software hackers denied being communists. Stallman thought up the slogan “free speech, not free beer” (Stallman, 2004) to make the meaning of “free” much clearer. The main reason why the manager of Microsoft called the free open source project a cancer was that FOSS projects were usually at no cost or low price. Therefore, the FOSS developer was also termed a “new sort of communist” even though the FOSS movement was not in principle opposed to commercialism in the field of the software industry. The companies that kept the source code closed could not compete effectively with FOSS projects when FOSS communities became a powerful movement producing a vast range

of software. Copyrights and intellectual property laws were invoked to protect the corporations' interests (Drahos and Braithwaite, 2002). The hackers damaged the intellectual property rights regime that served the cartels of information and communication technologies.

FOSS communities have been struggling with knowledge cartels over the question of copyright laws since the 1980s. Companies have generally licensed the software developed by their employees, and users cannot access the code of these products. Free software supporters in 1985 established a new strategy to deal with the obstacles arising from copyright laws. A new type of license, GNU General Public License (GPL), governing copyright, was introduced for the software industry. However, the aim of this license was entirely different from that of traditional copyright, which aimed to prohibit the copy, change, and distribution of software. Copyleft (and other open licenses) was a new type of license allowing users to distribute, modify, and exchange copies of software on condition that:

> Whenever you distribute anything that contains any piece of this program, that whole program must be distributed under these same terms, no more and no less. So, you can change the program and distribute a modified version, but when you do, the people who get that from you must get the same freedom that you got from us. And not just for the parts of it that you copied from our program, but also for the other parts of that program that they got from you. The whole of that program has to be free software for them (Stallman, 2002, p.172).

The struggle between the FOSS movement and corporations is not just related to the technical but also to the economic aspect of digitisation. In this sense, copyleft licensing can be seen as an important weapon that essentially empowers non-alienated and autonomous labour versus the capitalist mode of production based on alienated labour (Coleman, 2013; Soderberg, 2008). However, I think, copyleft licensing is not strong enough as a tool of protection against the capitalist system, because the corporations can use a dual license for FOSS and FOSHW products. In the next section, I shall discuss the new phase of hacking that adopts free open source philosophy for hardware projects.

The Rise of Free Open Source Hardware (FOSHW)

Peer production in hardware projects represents a new phase in the free open source movement (Sjöberg, 2016). The movement now includes deals in intangible goods, produced and distributed at virtually low cost but also tangible goods requiring raw materials. Although free flows of knowledge on the internet are still essential to the

production of the open source hardware design, the manufacture of open source design has created a new dimension for the hardware movement. Before looking at the ongoing discussions in this field, I need to explain the meaning of free open source hardware. The Open Source Hardware Association (OSHWA) defines open source hardware as:

> Open source hardware is hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design. The hardware's source, the design from which it is made, is available in the preferred format for making modifications to it. Ideally, open source hardware uses readily-available components and materials, standard processes, open infrastructure, unrestricted content, and open-source design tools to maximize the ability of individuals to make and use hardware. Open source hardware gives people the freedom to control their technology while sharing knowledge and encouraging commerce through the open exchange of designs (Oshwa.org, 2017).

The definition of open source hardware here includes “the design or hardware based on that design”. Open source hardware is a technology whose production is based on a community. It encompasses, on the one hand, production and distribution of software and designs, and on the other, the manufacture of devices. Hardware hacking is also dubbed “libre hardware” (Pearce, 2017) because it is based on free open source principles. Libre hardware is significant because it offers hackers several advantages. First, the cost of direct manufacturing equipment is lower. The lower cost of libre hardware puts pressure on the costs of proprietary hardware. Second, flexibility and customised equipment help improve experiments and speed the development of technology. Hackers can customise hardware to meet their exact needs. The ability to customise hardware for whatever hackers want is critical for technology users who seek to control the devices they use. Third, open source products might decrease the dependency of hobbyists on technology giants, as the latter do not allow users to modify products to meet their needs (Pearce, 2017). Proprietary companies do not disclose or share sources of hardware goods since these companies see closed source policies as protecting profitability. I argue that the intellectual property rights regime is not interested in the freedom of users, instead focusing on the high-profit margins of hardware. Hardware hacking, in this respect, can be a production model that respects the freedom of users by sharing sources of hardware with them. It is claimed that “the emergence of OSH results from the extension of the intellectual property management paradigm at work in Open Source Software (OSS) to physical products” (Bonvoison et al., 2018, p.1).

It is important to emphasise that the process of production and distribution of designs in FOSHW communities is quite similar to the method of production and

distribution of software in FOSS communities, and both are run at low cost on the internet. The FOSHW communities, however, are not just interested in hardware design, but also manufacture of hardware. It is clear that FOSHW goods cannot be manufactured on network platforms, and the manufacture of products incurs costs (Opensource.com, 2015). A physical place where makers or hackers can prototype tangible goods is needed, and this requires raw materials and sophisticated devices to be used in the manufacturing process.[40] The materials required for the manufacture of hardware products entail capital investments and local networks to build prototypes of free open source hardware designs. Table 4.1 illustrates the differences between open source software and open source hardware.

	Open source software	**Open source hardware**
Spatial	the virtual organisation, no production space needed	production space needed, travel necessary
Temporal	rapid development cycles (limited by number & skills of developers)	the speed of development cycles limited by access to physical resources and time of construction and copying
Social	Self–organisation with Internet tools	Self–organisation, but real-world resources needed
	several developers working in parallel on the same code	only a limited number of developers can work on a version, production of parallel versions costly
Economical	the raw material is free or owned by the developers	the raw material comes with a price, may be scarce
	the tools of production are free or owned by the developers	tools come with a price, may be scarce
	the end product functions as new raw material	the end product may be wasted, or otherwise removed from the productive cycle

[40] Those who make tangible goods for their needs at home are called "makers" (Dougherty, 2012). The maker movement is a new phenomenon. FOSHW is associated with the maker, as well as the hacker movement. The motivations of the maker movement are to have fun and acquire skills (Hatch, 2014), not unlike those of the hacker movement (see Torvalds, 2001; Coleman, 2013). Hackers and makers are complementary players engaged in the design, software and manufacture aspects of hardware products.

	perfect copies	copies as good as the person and machinery doing the copying
Evolutive	Linus' Law: • "Given enough eyeballs, are bugs are shallow" • rapid production of different versions • rapid pruning of mistakes and bad versions	• Bugs are potentially "deep" and de–bugging cannot be speeded up at will • production of versions takes time & resources • testing takes time and resources
	robustness and sustainability: can be forked at will, always already several competing versions	dependence on key resources and skills: forking takes time and resources

Table 4.1: The Main Differences between Open Source Software and Open Source Hardware (Malinen et al., 2011).

The ideal process for FOSHW can be explained thus: "Design global, manufacture local" (Kostakis et al., 2015) and "from mass production to production by masses" (Rifkin, 2014). Open hardware product design comes from a community of practice organised on the internet, and designers and developers may make contributions to the production of the digital part of FOSHW through network platforms.[41] [42] The main activities within CBPP, namely sharing, collaboration, and cooperation, are still instrumental to the production of design and software, but there are fewer hackers in hardware projects than software projects software projects (Malinen et al., 2011). Since hardware projects are much more complicated, the possibility of the fork of a hardware project is quite low.[43] Hardware hacking requires much more skill and experience than software hacking because it includes both hardware design and software development. Consequently, there is a small number of highly skilled experts involved in the production of hardware projects, but FOSHW communities can include thousands of contributing volunteers (Davidson, 2004). The motivations of hackers in hardware communities

[41] Taeyang Kim and Dong-Hee Shin (2016) state that FOSHW communities are goal-oriented prosumer communities.

[42] Open source hardware projects usually become electronic goods, so they also include software goods.

[43] Fork means that "a part of a development community (or a third party not related to the project) starts a completely independent line of development based on the source code basis of the project" (Robles and Gonzales-Barahona, 2012, p.2).

include fun, problem solving, reputation, signalling, learning and studying, identification with the community and altruism (Moritz et al., 2016). Piet Hausberg and Sebastian Spaeth (2018, p.4-13) state that “the more the makers feel an enjoyment-based intrinsic motivation, the higher their contribution to the OSH community”. They also add: “the more makers expect to improve their skills and to gain reputation through their work, the higher their contribution to the OSH community” and “when makers are highly motivated by reputational benefits and by learning benefits, the positive effect of enjoyment-based intrinsic motivation is bigger” (Ibid). To sum up, the key motivations of hardware hackers are having fun, improving skills, and gaining reputation.

Peer production for tangible goods is also conducted in physical spaces. Bonvoisin et al. claim (2018, p.27) that “distributed collaboration is not confined to the software components or documentation of OSH products but also applies to their physical components”. There are local physical spaces, instead of online communities, where makers come together and collaborate with each other to turn the designs into prototypes. These include fablabs, hackerspaces, or makerspaces (Braybrooke, 2019; Kemp, 2013; Baichtal, 2011; Liotard, 2017). Makers and hackers can use these spaces as platforms to effectively manage the manufacture of hardware projects, which require more complex means of production (Posch et al., 2010). In makerspaces community members can exchange experience of FOSHW production, technical kits or devices, which are otherwise expensive and complicated (Makerspaces.com, 2017, Powell, 2015).

Makers often employ desktop manufacturing and do-it-yourself (DIY) groups for the pursuit of FOSHW projects. In particular, free open source 3D printer, scanner and cutter projects enable the citizens to start the manufacture of hardware projects at home or in local places where there is no massive and expensive means of production (Rifkin, 2011; Anderson, 2012). 3D printing can be used for "functional models, artistic items, spare parts to devices, research/educational purposes and direct part production" (Moilanen and Vaden, 2013) and 3D printing technology is still in development. Kostakis et al. (2013, p.781) state that "3D printing customizes and localizes production, lowering the need for an assembly line, reducing transportation and the carbon footprint". New manufacturing tools have been computerised for a few decades, but they are now available in personal sizes for desktops (Anderson, 2013; Smith et al., 2013). Bernard Stiegler (2015, p.239) points out that "3D printers modify the modes of production". I argue that free open source 3D printers, are therefore important tools that modify the mode of production, benefitting all of society rather than a small number of tech giants.

3D printing could lead to the democratisation of hardware manufacturing. Rifkin states (2014, p.78): “the democratisation of manufacturing means that anyone and eventually everyone can access the means of production, making the question of who should own and control the means of production irrelevant, and capitalism along with it”. He (Ibid, p.79). also asserts, “the democratisation of production fundamentally disrupts the centralised manufacturing practices of the vertically integrated Second Industrial Revolution”. Clearly, open-source 3D printing is a growing player in desktop and hardware goods manufacturing, and the potential democratisation of production.

Use of 3D printers is a question of freedom for users. If the design and software of 3D printers remain open, users can customise them for their needs. The ability to change, modify or share design and software of 3D printers allows users to take control of technology, as opposed to powerless consumers. Stallman argues that:

> Printer patterns to make a useful, practical object (i.e., functional rather than decorative) must be free because they are works made for practical use. Users deserve control over these works, just as they deserve control over the software they use. Distributing a non-free functional object design is as wrong as distributing a non-free program (Stallman, 2019).

FOSHW, with desktop manufacturing and DIY, has the potential to lead a new industrial revolution, termed "The Third Industrial Revolution" (Rifkin, 2011; Anderson, 2012). This actually represents a critical phase in the digital era. On the one hand, FOSHW has emerged as a result of the advances in the digital transformation; on the other, it opens up the possibilities of hardware hacking to makers. FOSHW products allow citizens to manage the production and manufacture of tangible goods, which until recently were mainly controlled by corporations (Rifkin, 2014; Moritz et al, 2016). The FOSHW movement could make the means of production, for instance, 3D printers, affordable and physically manageable enough for ordinary users wishing to access the means to manufacture tangible goods (Moritz et al, 2018). In this way, ordinary people, and not capitalists, may seize the chance to be part of the production and manufacturing process of tangible goods without having to resort to large and expensive machines. Consequently, the potential changes in the production and distribution of tangible goods would have a knock-on effect on society and culture (see Kostakis et al., 2013). [44]

[44] It should be noted that relations of production play a vital role in the formation of culture and social relations. In industrial society, factories are the main places for the manufacture of tangible goods, and societies are divided into classes based on who owns factories and machinery and who does not (Marx and Engels, 1848).

The software industry has entered a new industrial phase through the internet of things. Clearly, this phase involves downsizing and cost-reducing the means of production, such as 3D printers and others. (Anderson, 2012; Rifkin, 2014). Desktop manufacturing has the potential to move production from factories, where capitalists lead the production process, to home-based manufacturing, which meets the needs of ordinary citizens (Lipson and Kurman, 2010; Hardt and Negri, 2017). In other words, home-based manufacturing can spearhead the production of tangible goods for use value, as hackers are not primarily interested producing for exchange value. Those with economic power derived from the accumulation of capital could lose this power and their dominant status if ordinary citizens were to have easy access to the means of production produced by the FOSHW movement. Heradio et al. (2018) explain that FOSHW products are used for educational purposes. Open hardware can improve methods in teaching, providing students with an experimental resource to understand themes in engineering and science. FOSHW can also reduce laboratory costs. Open-source 3D printing in particular can play a key role in the manufacture of cheaper experiment kits. Open hardware products promote students' interest and engagement. Lastly, simple FOSHW products are also used to foster learners' creativity and support distance learning.

FOSHW is the last phase of hacking history (see Jordan, 2017). With FOSHW, hackers have brought digital development into the hardware field, where ordinary citizens can gain access to technological devices and to new means of production that in turn reduce costs and accelerate hardware innovation (Gupta et al., 2016; Pearce, 2015). In this way, FOSHW products are centrally positioned in the democratising process (Powel, 2012). Hackers become influential players in the FOSHW movement, symbolising the growth of a new culture. Taeyang Kim and Dong-Hee Shin (2016, p.217) assert that FOSS "has changed the way many tech companies do business and has therefore changed our society" and they (ibid) also add FOSHW "is an attempt to bring the same freedom and power to physical devices". Apart from being producers of technology, hackers have led important cultural developments notably by supporting the freedom of users, the free flows of knowledge, and peer collaboration. With FOSHW, hackers or makers allow ordinary citizens to manage the manufacture of hardware projects at home. In other words, the manufacturing process might shift from large factories controlled by the capitalist class to citizens' homes. The means of production is in the hands of the capitalist class; its liberation, and popular access to it thanks to FOSHW, corresponds to the democratisation of production of tangible goods (see Mota, 2011). FOSHW products are

often much cheaper than those of private companies. Hackers can play a vital role in the reduction of hardware product costs. I argue that hackers in FOSHW communities, with their technical skills, are key players in the creation of a new culture based on collaboration, cooperation, and sharing practices.

The FOSHW movement applies copyleft to prevent the design and software of hardware from being turned into a closed source. Copyleft licenses comprise the GNU General Public License (GPL), Creative Commons Attribution- ShareAlike License. There are also some open licenses that have been designed specifically for hardware: the CERN Open Hardware License (OHL) and TAPR Open Hardware License (OHL). According to a survey, the majority -70%- of open hardware projects use the Creative Commons, which covers digital works of authors and artists, while only 17% of projects use proper open hardware licenses such as CERN, OHL and TAPR (Moritz et al, 2018). Hackers in FOSHW communities can also use licenses for their hardware goods. These licenses include the Creative Commons Attribution License, the FreeBSD License, the MIT License and The Solderpad Hardware License (Oshwa.org, 2019) Apache 2.0 is another license that allows users to make changes (Stallman, 2019).

As explained before, FOSHW projects consist of artistic works, such as design and software, and knowledge used for functional works, such as prototyping and manufacturing. The former can be covered by open licenses, while the latter is usually covered by a patent, which governs commercial activities with tangible goods. (Hausberg and Spaeth, 2018). Applying for a patent is time-consuming and expensive. The most important issue with the patent is that it is not compatible with open source policies. Defensive patenting, which does not contradict open licenses, is a significant issue for discussion in FOSHW communities; there is no open, widely used patent in communities as yet. Trademarks used by the companies and projects constitute another tool of IPR in the protection of commercial interests, controlling the distribution of trademarked or branded open hardware products (Moritz et al., 2018).

FOSHW has similar drawbacks to FOSS when it comes to the structure of the community, the decision-making process, and the sharing of values within the community. In addition, FOSHW requires much more raw material and energy. Consequently, the mass manufacture of hardware products would require capital investment. Seemingly, there are two ways to gain the investments needed. The first is for the market economy to supply sufficient investment in exchange for making a return on the projects (Gupta et al., 2016). The implication is that the FOSHW movement, a

CBPP model based on the production of tangible goods, could become an instrument of the market economy in which exchange value overrides use value. This is obviously a dilemma for the FOSHW movement. Although it does not oppose hackers making money from FOSHW products or services in return for their labour power, profit-based production undermines the commons-based ecology where peers collaboratively build digital devices. The other way is for the movement to form cooperatives to manage the manufacture of hardware along non-profit lines (see Scholz, 2015). Kostakis et al. (2013, p.782) emphasize that "the expansion of CBPP practices into physical production could arguably create networks of individual producers, cooperatives, nonprofit foundations, and for-profit companies which would work globally but produce locally". FOSHW can become either non-foundation and cooperatives-based or for-profit companies-based. Hackers in FOSHW communities can have either a for-profit or non-profit motivation when supporting an open hardware project.

The meaning of "free" is still ambiguous in hardware projects. Moreover, the meaning of "open source" is also quite ambiguous because FOSHW has a manufacturing process. Open source is defined as keeping code open for software products and can be defined as keeping hardware designs open. But it does not keep material or tangible goods open for the manufacturing process. Arguably, the meanings of "free" and "open source" are much more ambiguous in FOSHW than in FOSS.

FOSHW, however, faces certain challenges in its access to raw materials, in the organisation of the manufacturing process locally, and in sharing economic value (money) in the community. As stated previously, the production and distribution of designs and software can be at low cost on the internet (Rifkin, 2014); however, the manufacture of hardware projects requires raw materials, technological devices, and a great deal of energy. As such, FOSHW projects generally requires more investment than FOSS projects. This once again raises the important question of tensions between commons and market. Moritz et al (2016) assert that commercial affiliates are important partners of open hardware projects in the manufacturing of hardware goods. The requirement of capital investment in the manufacture of the hardware enables capitalists to make a profit from FOSHW projects. The profits of capitalists, in this context, are mainly based on the exploitation of volunteers' and developers' creativity. The sharing of values created by free open source communities is a very vague issue. The owners of the project and commercial affiliates can make money from their products while volunteers typically cannot make a living directly from open hardware projects in return for their

productive fun labour. Fun labour can be an effective element to help FOSHW projects reduce production costs. Moritz et al. add that:

> Prototyping of the GVCS [Global Village Construction Set] machines is the most expensive matter of expense (77 %) followed by personnel costs (15 %). Overhead, travelling, fuel, and other expenses play a minor role (8 %). The costs structure highlights the importance of voluntary collaborators for the advance of OSE [Open Source Ecology] (2016, p.2373).

Voluntary labour on the one hand helps reduce the price of open source hardware, and people can gain access to technological tools cheaply. The appropriation of fun labour by project owners on the other hand can give rise to hyper-exploitation, increasing inequalities and injustices between groups in hardware communities. Lisa Eccles (2001) asserts that "open-source hardware library will consist of design elements for processors, memory controllers, peripherals, motherboards, and other components… device manufacturers will be able to use this library to gain useful design information and license designs for free". Manufacturers can use software and design created by open source communities without having to pay and then make profits from the products developed by the communities. Value sharing in the community is highly problematic, some benefiting financially from open source products, others not. Many open source projects are led by open source companies that sell the commodities produced by the free open source communities (Gewirtz, 2016). The production model of these companies is still based on the CBPP model, but these companies oversee the distribution and sale of FOSS products and are usually run by CEOs.

FOSHW communities also consist of developers or designers, and volunteers. As previously mentioned, the leader can be like a benevolent dictator, wielding decision-making power, assisted by their co-developers.[45] However, volunteers, the largest group in the communities, seldom have the right to participate in the decision-making process and do not usually receive a share of the value created by the communities. In short, there is a tension in FOSHW. Open hardware communities might allow ordinary citizens to access the means of production, an essential factor allowing the masses to become contributors to projects via the CBPP model.[46] Conversely, these movements can also create social inequalities in the communities, through the exploitation of developers'

[45] Kostakis et al (2013) claim that abusing the power in CBPP communities by benevolent dictators often happens and gives rise to an exodus of community members, but peers have an opportunity to start a new project based on CBPP.

[46] FOSHW projects enable people to participate in the production process, which is a public activity (Kostakis et al, 2013).

voluntary labour by group leaders or companies. Additionally, most developers do not play an active role in the decision-making process of communities.

In this chapter, I have examined the term hacking and the roles of hackers. I have also looked at how the hacker movement has evolved over the years. I then focused on the issue of open source communities and the issue of intellectual property rights. Lastly, I explored the rise of FOSHW. In the final sections, I discussed the opportunities and challenges of hardware hacking. In the following chapters, I will focus on two significant FOSHW communities: RepRap and Arduino.

Chapter 5: RepRap as a Free Open Source Hardware Project

In this chapter, I discuss some issues relevant to FOSHW communities by looking at the case of RepRap empirically. As previously stated, RepRap is a self-replicating 3D printer, a popular hardware project in the hacker and maker movements that lead desktop manufacturing. Analysing RepRap, I argue, can yield significant insight into the FOSHW movement.

This empirical chapter consists of two main sections. The first outlines the history and basic characteristics of RepRap. The second section examines key questions in the RepRap community. I apply corpus and thematic analyses to the data gathered from the RepRap developers' mailing list archive and interviews.

Background to RepRap

RepRap (short for replicating rapid prototype) is a community where developers have created a free open source desktop self-replicating machine capable of printing its components. Michael Stanko (2020) asserts that RepRap is an online innovation community. Many parts of the machine consist of plastic (RepRap.org, 2018a; Jones et al., 2011). It is possible for anyone with a RepRap machine to print a new self-replicating 3D printer for their friends. The RepRap community encourages hackers and makers to create a new machine or device that can copy itself and might be made at low cost available to members of the community. Without doubt, self-replication is the most significant characteristic of the RepRap 3D printer. Conventional industry does not lean towards the idea of self-replicating prototypes since this idea does not provide the companies with sufficient incentive to make a profit. 3D printing companies usually prefer to sell devices they produce for commercial interest. However, self-replicating devices enable customers to manufacture new machines for people around them instead of having to buy another one from the companies. RepRap, for this reason, has been developed under the free open source production model supported by the GNU General Public License (GPL) since 2004 (Bradshaw et al., 2010).

RepRap was also the first cheap 3D printer and led the development of free open source 3D printing. It is the most popular 3D printer in the maker movement (RepRap.org, 2018a). Figure 5.1 shows the popularity of RepRap in the maker movement.

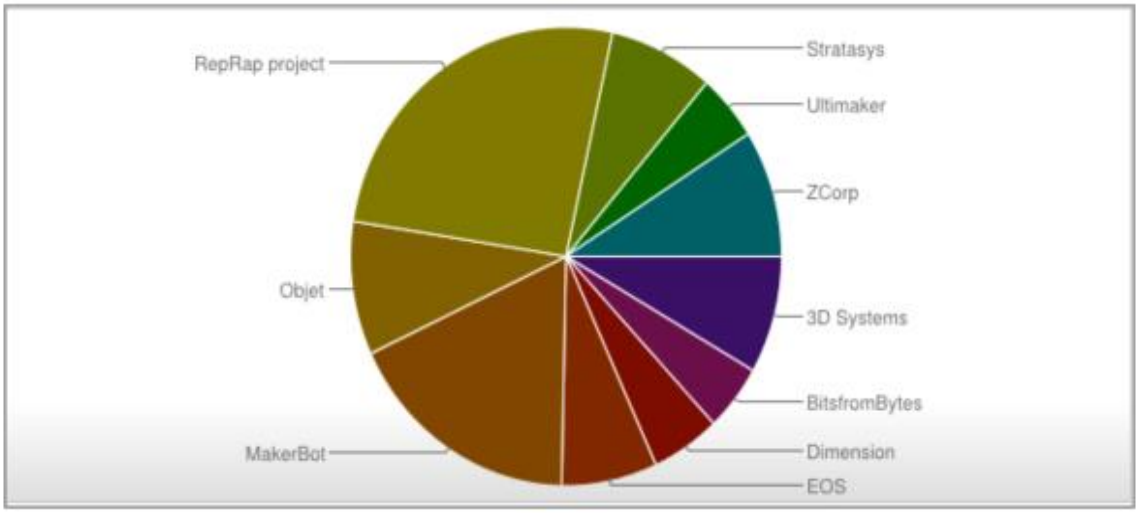

Figure 5.1: The Popularity of RepRap in the Maker Movement. (Moilanen and Vaden, 2013).

The RepRap machine was invented in 2004, by Dr Adrian Bowyer, a senior lecturer in the field of mechanical engineering at the University of Bath, but the project then evolved through the peer production model. In 2005, the RepRap blog was created, and contributors to the blog collectively developed the idea of the self-replicating machine. The core contributors of the blog consisted in the early years of Adrian Bowyer, Vik Oliver, Ed Sells, Simon Mc Auliffe, and Forest Higgs (see Hodgson, 2012). The RepRap community has amassed a considerable number of contributors and users around the world since 2005. Table 5.1 illustrates a brief history of the RepRap project.

2004	RepRap was invented by Dr Adrian Bowyer
2005	The RepRap Blog was founded, and research started. Funding for the initial development of RepRap at the University of Bath was obtained from the Engineering and Physical Science Research Council
2007	The first RepRap Darwin was completed. Polylactic acid (PLA), a material for 3D printing, was introduced by Vik Oliver.
2008	Darwin successfully replicated over half its parts. It was announced that at least 100 copies of Darwin had been produced around the world.
2009	The second-generation RepRap, called “Mendel”, was completed. MakerBot Industries, the first company, was established by RepRap contributors to sell 3D printers based on RepRap but not self-replicating. RepRap Ltd was founded

	by Dr Adrian Bowyer to support the development of RepRap projects.
2010	Huxley, the third-generation design of RepRap, was introduced
2011	Prusa i2, the fourth-generation design, was announced. Aleph Objects, a 3D printer company based on RepRap, was founded.
2012	Prusa i3 was introduced. Use of RepRap raised in hacker and maker communities. The first Delta RepRap Design was developed.
2015	The RepRap snappy was developed. This was the most self-replicating 3D printer, producing 73% of itself.
2016	RepRap Ltd started selling RepRap 3D printers and components.

Table 5.1: A Brief History of RepRap Development. (see RepRap.org, 2018b; Hodgson, 2012; All3dp.com, 2016).

Bowyer (2011) claims that the replication rapid prototyping machine has a revolutionary potential allowing the proletariat to own the means of production.[47] However, the revolution will not be carried out with typically political or industrial "dangerous stuff". Bowyer believes that political uprisings or conflicts between social classes are "dangerous stuff" that have detrimental effects on society. He dubbed the process of RepRap development as "Darwinian Marxism" since the changes in the ownership of the means of production on behalf of the proletariat will progressively emerge as a result of the rise of the number of self-replicating machines. The process will be made up of three stages:

1- The number of them [RepRap 3D printers] in existence and the wealth they produce can grow exponentially.
2- The machine becomes to evolution by artificial selection, and
3- The machine creates wealth with a minimal need for industrial manufacturing (Bowyer, 2011).

It is claimed that self-replicating 3D printing can lead to new relations of production where the production and manufacture of goods will occur following the logic of "wealth without money" (see Bowyer, 2011). This statement seems quite radically anti-capitalist since the capitalist mode of production is based on the accumulation of capital. The main motivation of capitalists is to make increased profit from the production of commodities

[47] The proletariat, in this case, refers to ordinary people using technology.

(Marx, 1990). In this respect, wealth refers to capital or profits in capitalism. However, "wealth without money" is the purpose of self-replication machines, as Bowyer explains,

> …a self-copying rapid-prototyping machine can make one copy of itself a day, and also just one comb. After merely 18 days, the rapid-prototyping machines will be making more combs than the injection moulder, assuming people give them house-room. Self-copying rapid-prototyping machines can multiply exponentially and so can the goods they produce… People may just have their machine copy itself, or they may improve the design (and its firmware) and have their existing parent machine make their new, and better, child machines instead. That's how we made a labrador out of a wolf. Thus the machines will improve; good designs will come to predominate, and the lesser ones will fall by the wayside (Bowyer, 2011).

The RepRap 3D self-replicating printer is seen as a tool heralding a new mode of production for technology (Ibid). People theoretically create a support network in which they can share the components of self-replicating machines and designs with each other. The infrastructure of the internet allows users to share software and design of RepRap 3D printers. It does not matter whether designs and software are sold or not. Even users pay to an extent for designs/software or raw materials, as this is still cheaper than buying a 3D printer from a big brand name.

Self-replicating machines enable free collaboration and creativity, and hackers can manufacture their 3D printers at home based on the design developed by the community. Self-replicating machines, in this sense, promote the creative activities of hackers in the manufacturing process as these machines allow hackers to customise their machines. Hackers extend collaboration and cooperation to both offline and online communities. They do not just share intangible internet goods such as software, design, knowledge and so on; they also share self-replicating machines with others for further replication. It seems that hackers have significant autonomy in the design of their 3D printers when manufacturing their tools with these machines. Therefore, there is a distinct range of RepRap projects with different designs, size, components, materials and so on (RepRap.org, 2019).

The RepRap community does not have a standard design for 3D printing (Stanko, 2020). Hackers can develop their designs, and prototype them, without having to seek permission. As I said before, commercial manufacturers can benefit from design and software produced by open source communities to make a profit. In hacking hardware, the manufacturing process requires raw materials and means of production. As 3D printers are viewed as a new sort of cheap, portable productions tool; hackers will likely need or want to buy one. It does not matter whether 3D printers are open source or not.

With self-replication, hackers can provide the members of the RepRap community with production tools to manufacture hardware goods locally. Following this production model, there would be no need for a company to manufacture and sell 3D printers. It is difficult to standardise the creativity of hackers under this production model because there is no centre, or top-down management model directing the production process. Self-replication thereby promotes decentralised and non-profit production, as the productive fun labour of volunteers is not exploited by the corporations.

The first RepRap machine design was named "Darwin", who was of course the father of evolutionary theory. Evolution is a significant term for the RepRap community because the development of the RepRap 3D printer is based on an evolutionary process where many people partake in the mutation of the self-replicating machines. Each change made is a small contribution from one or more of many contributors to the community. Bowyer adds:

> This [evolution of RepRap] is almost the same as Darwinian evolution, but with one important difference: in nature, mutations are random, and only a tiny fraction are improvements; but with self-copying rapid-prototyping machines, every mutation is a product of analytical thought… It also means that people of modest means will be able to own them, and also let their friends have copies. They will be able to make themselves a new flute, a new digital camera, or just a new comb by downloading the designs for them from the Web (Bowyer, 2011).

The community, furthermore, created a loaner program in 2010 and a union, called RepRap Union, in 2011 to share tangible parts of the machines. The loaner program allowed users to borrow parts of the RepRap 3D printer from the owners of self-replicating machines. People used the borrowed self-replicating devices to build at least one machine and then return the machine to the owners. There were some rules attached to the loaner program: 1-) the loaner's printer to be returned to the owner on time; 2-) a refundable deposit system should be created to keep things moving. The loaner program was intended to empower collaboration and cooperation among members of the RepRap community. The loaner system was to be non-profit. 3-) RepRap was accepted as a compassionate act (RepRap.org, 2018c). The loaner system also encouraged people to build more than one self-replicating machine, and if possible, at least one of them to be donated to "the commons", which referred to makerspaces or hackerspaces (RepRap.org, 2018c). RepRap union or spaceXULA union was another kind of loaner program, but it was for hackerspaces or groups of users, not individuals (RepRap.org, 2018d). However, the loaner program or RepRap Union did not work well and failed to create an effective

network system for peers to share the machine parts with others. The failure of the loaner program posed an important challenge to the FOSHW movement.

Reproduction and sharing of intangible goods, including software, design and knowledge, are at almost zero cost on the website, but the procedure of sharing machine parts is much more complicated than that of software or design. The reproduction and sharing of tangible goods are quite costly because tangible goods such as 3D printers need raw materials and energy for their manufacture. Therefore, people require finance to manufacture and share parts of 3D printers with others. It is impossible to share tangible goods on the internet; people must pay for the distribution of hardware, as well as a refundable deposit to the machine owners. The process is a little complicated and time-consuming. This could be the reason why RepRap users have lost interest in the loaner system.

Another interesting invention of the RepRap community is Polylactic acid (PLA), from which polymorph, friendly plastic, CAPA, instamorph and shapelock. It has been an important material for the RepRap 3D printer since the first "child" RepRap project was replicated by PLA filament. Vik Oliver, the first RepRap volunteer, utilised PLA as a material for the self-replicating machine in 2007. PLA is a material with a low melting point, about 60 °C. Such materials facilitate the operation of 3D printers. The RepRap community has contributed to the digital era, not just with the invention of the self-replicating 3D printers, but also in the use of PLA as a raw material for 3D printers. Today, most 3D printers rely on PLA and ABS (Acrylonitrile Butadiene Styrene), the lowest-cost raw materials, to manufacture goods (RepRap.org, 2018e). PLA is more environmentally friendly than other materials used for 3D printing. It also has a higher 3D printer speed and does not emit harmful fumes (Flynt, 2017). PLA enables makers to build a more environmentally friendly technology around the world. The low-cost raw materials are important to the development of RepRap 3D printing in the hacker and maker movements. Furthermore, free open source self-replicating machines and cheap raw materials allow not just ordinary people but also developing countries to engage in digital production. RepRap 3D printing with PLA threatens to close the digital divide between people from diverse social and regional backgrounds.

RepRap projects are now around 15 years old. There are currently a great variety of RepRap 3D printers available internationally. The companies created by RepRap volunteers sell some of them. For example, Josef Prusa created a company to sell his RepRap machines. The cost of RepRap Prusa i3 MK3 kit is £699. RepRap Ltd, created

by Bowyer, sells RepRap fisher delta 3D printer kit for £220-£250. However, the RepRap 3D printer kit can be bought separately from different suppliers. The cost of building a RepRap machine in the US was between $300 and $620 in 2014 (see RepRapltd.com, 2019; Prusa3d, 2019).

Free open source 3D printers are usually cheaper than those of proprietary companies. The most inexpensive MakerBot 3D printer is the replicator mini+ compact 3D printer at $ 1,299. It is more expensive than any type of RepRap self-replicating machine. The story of the MakerBot 3D printer company is also quite striking. The company was initially founded by RepRap volunteers in 2009 to sell free open source self-replicating machines. However, MakerBot was turned into a proprietary company within a couple of years of being founded. In 2011, The Foundry Group invested around $10 million in MakerBot and joined MakerBot's board (Feld and Thoughts, 2011). In 2012, Zachary Smith aka Hoeken, one of the founders of MakerBot, was pushed out of the company after a dispute over the company's key policies. He was insisting that the company continue to follow open source principles, and objected to the merger of MakerBot with Stratasys, a proprietary company. Smith lost the fight, and MakerBot abandoned free open source principles. Around 100 employees of MakerBot were fired at the same time (Pearson, 2015). In 2012, MakerBot started to pursue closed source policies. This was a low point in the history of the free open source movement and the RepRap community. Aka Hoeken claimed that MakerBot's shift from open to closed source was a betrayal of the free open source movement. He added,

> If these allegations [turning into closed source] do prove true, it would be a sad day indeed for the open hardware movement. Not only would it be a loss of a large Open Hardware manufacturer, but it would also be a loss of a poster child for the movement. Many people have pointed at MakerBot and said, "Yes, OSHW is viable as a business model, look at how successful MakerBot is." If they close those doors, then it would give people who would say OSHW is not sustainable ammunition for their arguments. It would also discourage new OSHW companies from forming. That is a sad thing indeed (Aka Hoeken, 2012).

The story of MakerBot is significant because it exposed conflicts in the community over commercialisation of FOSHW projects and RepRap 3D printers. MakerBot attempted to create an open source friendly business model and made profit from products based on RepRap. However, the company turned into a proprietary company. Why did a successful open source-based company fail to follow free open source principles? The main reason, I argue, was that the owners of the company sought to profit from the closed source 3D

printer industry. However, open source principles were seen to stand in the way of this profit making. The company based on open source makes lower returns than the company selling closed source products.

According to a list showing the top ten 3D Printing Companies in the industry, none of them is open source (see Kay, 2018). Today, at least, closed source companies are still making much more money than open source companies. This is the nature of big business, in technology as elsewhere. In this way, open source-based business is squeezed by the tensions between the commons and the market in the community. There is a dialectical contradiction in the RepRap community: on the one hand, the community helps users to manage the production and manufacturing of self-replicating machines; on the other the products created by the community are appropriated by companies for commercial gain. Even though the companies do not play a key role in the production of design and software, they make a profit from the design and manufacture of RepRap 3D printers, and not self-replicating machines. Hackers are not usually paid, their productive fun labour is exploited by the corporation- a hyper-exploitation process taking place in the community (Kostakis and Bauwens, 2014; Harvey, 2017).

The commodification of knowledge can be highly profitable in the field of technology. However, free open source products are usually distributed with copyleft-type licenses. Consequently, the flow of FOSS and design cannot easily be controlled on the internet. Users can freely modify, change and share the design and software of FOSHW products. The open source friendly business model might not make huge profits on intangible goods as the commercialisation of free open source software/design proves to be more difficult than that of closed source products. The companies based on open source principles, for this reason, struggle to compete with the companies selling closed source products. Open source business is a commercial model seeking to reduce the tensions between the market and the commons. But this model did not work in the case of MakerBot; investors put the company on a new path that dismissed the principles of the commons and community-based production.

There are still a number of 3D companies based on RepRap besides MakerBot. However, the story of MakerBot shows how capitalists can manipulate the principles of open source when they take control of a company board, since capitalists, as investors, only ever care about making a profit; they are not interested in the democratisation of technology production. On this point there is a fundamental tension between the commons and the market. Even though open source 3D printing companies benefit from

the design of RepRap, these companies mostly focus on the sales of open source 3D printers. None of them is interested in the issue of self-replication even though RepRap is known to stand for self-replicating machines. Self-replication is an important in community-based production as hackers do not need to resort to the market or bazaar to acquire a tool of production. However, as the open source 3D printing companies need to sell as many 3D printers as possible, they are not keen on the development of self-replicating machines.

Josef Prusa (2012) claimed that the design of MakerBot was based on a RepRap design, but MakerBot received a patent for the design from the RepRap project (Brown, 2012). The design produced by contributors and developers of the RepRap community became the private property of the MakerBot company. This paved the way for an exploitative process where the labours of developers and volunteers in the RepRap community served the accumulation of capital for MakerBot without the payment of wages to RepRap contributors. The company also applied the commercial Qt license for new versions of design and software of MakerBot to by-pass the obligations of copyleft or open licenses (see Prusa, 2012).[48] The productive fun labour of hackers appropriated and exploited by the MakerBot company is one of the most important challenges faced by the RepRap community. Profit-oriented production caused a terrible crisis in the MakerBot company, leading the company to halt production of open source 3D printers; it turned into a proprietary company producing and selling closed source products. Moritz et al. (2018, p.201) state that "MakerBot started selling kits and ready-to-use printers that were based on the RepRap works. Within 3 years, MakerBot sold 22,000 3D printers. Finally, MakerBot was sold to Stratasys for more than $ 400 million as the market for 3D printers exploded". The creativity of volunteers and developers in the RepRap community created huge value in the market, but they themselves failed to benefit from this value instead business capitalised on it.

The RepRap community mostly relies on the GNU General Public License (GPL) to protect its legal rights; it is against patented technology (RepRap.org, 2016). GNU GPL is a copyleft license which allows users to modify, share and change products on condition that users always keep all sources open. Even the source of a modified version of a product must be kept open. In this way, the license allows people to operate an open

[48]The commercial Qt license "is dual license under commercial and open source licenses. The commercial Qt license gives you the full rights to create and distribute software on your term without any open source license obligations" (Qt.io, 2019).

source friendly business, but the license does not permit proprietary commercialisation of free open source production (Gnu.org, 2019). However, companies can find ways to by-pass copyleft licenses, just as the MakerBot company did.

Analysis of the RepRap Community

Corpus and thematic analyses are applied in this section. The members of the community, such as developers, designers, and users, are crucial not only to the production of hardware projects, but also of social and cultural goods in the community. The advocates of the free open source movement play a key role in the ideological debates. Thematic analysis helps to identify repetition, resurgence, and forcefulness in cultural or ideological stratifications (Lawless and Chen, 2019). The community discussions of RepRap hackers give us important clues as to the social and ideological backgrounds of that community's members. The RepRap developers' mailing list was one of the most popular communication platforms among RepRap developers and designers between 2010 and 2016. The discussions on the mailing list archive provide us with fruitful data for the application of corpus analysis and thematic analysis.[49] I interviewed several members from the RepRap developers' mailing list. The data gathered from the interviews is also used in my thematic analysis.

The RepRap developers' mailing list archive has yielded a large amount of data. Therefore, I have categorised the list data with AntConc, a corpus analysis tool. Corpus analysis has provided me with a list of words, including 50 popular stemmed words used by the developers on the list. (see Appendix 1). I have compared the RepRap mailing list with the British National Corpus world list to calculate the keyness of the keywords, which shows the frequency of the words that are domain specific to the mailing list.

The most frequent words, including "firmware", "extruder", "printer", "machine" and "make", constitute vocabulary used in the production process of FOSHW projects. Additionally, these words can be seen as part of the technical discourse of hackers. The developers usually explain how software and machines make, assemble, print or fix on the mailing list. Some words such as "sell", "commercial", "cheap" or "cost" are more closely related to the commercialisation of RepRap projects. For the legal protection of RepRap projects, "patent" or "license" is often discussed by developers. After examining

[49] Hundreds of developers and volunteers in the RepRap community gave up their creativity and free time on the mailing list so the mailing archive included rich data to analyse social and cultural aspects of the community.

the result of the corpus text analysis of the RepRap mailing list and reading the interview transcriptions, I coded primary source, and identified themes that were useful categories in the analysis of qualitative data. The preliminary themes identified in this thematic analysis within the discussions of RepRap hackers were: “the issue of open source”, “the issue of self-replicating”, “customisation”, “intellectual property right tools” and “fun in the RepRap community”, “the structure of the organisation” and “collaboration in the RepRap community”. Before analysing the identified themes, I will give some details about the demographic backgrounds of the interviewees given that the data collected from the interviews is also used for thematic analysis. The demographic backgrounds of people are an important factor in the analysis of power relations.

Eleven developers, members of the RepRap developers’ mailing list, contributed to the interviews; some of them were among the ten most active members on the mailing list. All interviewees were male; I did not meet any female hackers from the list. It was clearly male dominated. Most developers were highly skilled and educated developers from developed western countries. The youngest developer was 39; the average age of the interviewees was 52 (see Appendix 2). This average would seem high for a hacker community, but some of these developers have been in the hacker movement since the 1970s. They had great experience of the development of software and hardware aspects of electronic devices. Now, it is time to focus on the key themes.

1-The Issue of Open Source

Open source: In fact, the concept of open source has been a topic of discussion for more than two decades within the OSS movement. The concept has generally been understood as keeping all source code open. However, hardware projects do not consist solely of code or design, but also tangible goods. It is clear that hardware products require much more source (tangible and intangible); thus, the production and distribution of hardware products are more complicated. Open source is a critical concept in the RepRap community. Developers describe “open source” in the following terms:

> The open source and open hardware in my world are - I share what I do, I learn from what other people did, and while we are sharing our knowledge, and our experience, we all improve ourselves and move towards some common goal (interview with ReRM02).

> Open source, hardware or software, is the opportunity to learn from others. To see how they solved problems, the ability to copy the solutions. This frees up time for own developments and improvements. Providing my own work

> to the public is often answered with reviews, suggestions, sometimes even usable contributions (Interview with ReRM03).

RepRap developers place open source alongside “learning”, “sharing” “knowledge” and “experience”, “improvement”, “suggestion” and “contribution”. In particular, the statement, “providing my own work to the public”, shows that there is a strong relationship between commons and open source for developers. The term open source refers to the digital commons where developers can share their experience and knowledge to improve or develop a free open source hardware project. The reviews and suggestions can be also seen as useful contributions, voluntary labour in the production of digital goods. Hackers essentially contribute their voluntary labour to projects because being a part of the production process allows hackers to develop their skills and learn new techniques in the production of FOSHW. “It [open source] gave me a chance to upgrade my skills to do things that I haven’t done before” (interview with ReRM09).

One of the most striking points in the quotation above is that all explanations of “open source” relate to intangible goods only. Sharing practices include knowledge, experience, design, code or suggestions; for the most part they do not involve machines, machine components or devices. The RepRap community has discussed the RepRapUnion enabling community members to share their 3D printers with other peers in the reproduction of new printers or a component of a printer. The only thing the users require is a working self-replicating machine, raw materials, and energy. However, the respondents never mentioned these things during interviews. The concept of open source applied only to intangible goods. Open source is also seen as an alternative solution to closed source hardware.

> Open source hardware is a community effort in creating a device which would serve a set purpose, most probably an alternative to an existing commercial device which is expensive or doesn't allow any modifications to be made. This lack of flexibility for closed source hardware could create a mismatch between what the user requires and what the device provides which would invariably lead to alternative solutions (ReRM41 from the mailing list).

“Alternative/solution” here implies inexpensiveness and flexibility. Even though some followers of the open source movement avoid using the concept of “free” with respect to price or cost, open source still implies cheap or free products. In the RepRap community, some developers think that there is a relationship between open source and reduced 3D printing costs:

> I thought the goal of the project [RepRap] was to reduce the cost of 3d printing. Plastic 3d printing was reached by two magnitudes. When we started

> the project, the turnkey cost of setting up a 3d printer was about 40,000 dollars, and we were shooting for 500 dollars, so we got that […] in 2010, 2011 and so it was very fulfilling in that sense (Interview with ReRM09).

> RepRap is like any other open source project. The cheapest solution is likely to be the best tested (ReRM10 from the mailing list).

Flexibility means the ability to change and modify FOSHW products. However, closed source products do not allow users to change source code or design given that they are not shared with users. The companies that produce closed source software and hardware do not wish users to take control of the products. One of the differences between open source and closed source is that users can take control of open source product while closed source does not allow this. Accordingly, the right to change or modify technology becomes a question of user freedom, because ICT companies limit this with their closed source policies.

Another interesting discussion topic on the RepRap mailing list is advertising. Some developers criticise the policies of the RepRap website that allow ads for proprietary goods on the website of an open source hardware project.

> Why is there advertising on Reprap.org? The Google ads are very poor form for a non-profit academic open source project. It breaks my heart… Advertising, unless it is for a grant or award is *necessarily* for profit. The RepRap project and the RepRap site are strongly committed to non-profit ideals, to the strictly enforced exclusion of for-profit postings. Therefore, putting advertising on a STRICTLY non-profit site is totally bonkers (ReRM16 from the mailing list)

There has been an interesting tension among developers on the RepRap mailing list regarding ads on reprap.org. The ads are related to closed source products, and one of the developers has objected to such ads on the website. However, the most striking thing is that the developer calls the RepRap project "a non-profit academic open source project". As I discussed in the previous chapter, in principle the free open source movement is not against the commercialisation of free open source products. Developers can sell their free open source self-replicating machines to users or manufacturers as long as they continue to keep all sources open and share all sources with their customers. However, it seems that there is still no consensus on the relationship between the free open source movement and the commercialisation of RepRap.

RepRap Prusa is an open source 3D printer company, not a non-profit project, because the company makes a return on free open source products (Peels, 2018).[50] The discussion about ads shows that the relationship between the commons and the market still provokes tensions within the RepRap community.

Being non-profit, and anti-capitalist are two different things.

> RepRap.org and the wiki generate costs. Also, Adrian [the leader of the community] does have an airplane, beer, and pizza costs. These require some form of revenue stream for the organization. The team has chosen to take on modest advertising instead of asking for donations constantly (ReRM23 from the mailing list).

Hackers in the free open source movement can have different ideological backgrounds. The tension in the RepRap community around ads is indeed derived from ideological differences. Being non-profit and anti-capitalist not the same thing. However, those who have trouble with the commodification of knowledge may not want to see closed source product ads on a project they support as these ads serve the commodification of knowledge. The developer may in principle oppose the advertising of closed source products, but they do not necessarily have an anti-capitalist orientation, firmly opposed to selling open source products for profit.

The ideological differences between hackers show up in the discussions. Some developers support the idea that open source should be organised through non-profit structures geared towards the use value of free open source products. Hackers should focus on the quality or flexibility of free open source products rather than on their commercial value. “This is a community project to improve open source 3D printers and bring the technology to everyone” (ReRM45 from the mailing list). These developers are generally close to communitarian or egalitarian ideas, and often oppose the marketisation of free open source products. Nonetheless, free open source RepRap 3D printing has created a business opportunity, and some developers have formed companies based on RepRap projects, including MakerBot (in the early years), Prusa and Ultimaker,

There is an ongoing struggle between RepRap developers to fix the meaning of open source. Open source is still not a fixed idea, and hackers in the RepRap community might assign different meanings to the concept. For hardware projects, in my view, open source includes sharing code, designs, knowledge, and experience; not manufacture.

[50] Josef Prusa was one of the most active developers in the RepRap community who formed an open source 3D printing company. Prusa got a significant reputation in return to his contributions to the community. He also developed his 3D printer design and made money from his design. Getting a reputation in the community turned into money eventually.

Acquiring skills and learning new techniques are key elements of the free open source production model for many developers. However, there is a significant tension between hackers over the political economy of free open source projects. This tension shows up in the discussions on the mailing list, drawing on the tension between the commons and the market. The tension between "non-profit" and "commercial" reveals an ideological struggle between hackers.

2-The Issue of Self-Replication

Self-Replication: The replicating rapid prototyper (RepRap) is a self-replicating manufacturing machine. This means that the machine can self-replicate by making a kit of itself that consists of plastics; it also means "if you've got a RepRap - you can print lots of useful stuff, and you can print another RepRap for a friend" (Reprap.org 2018a). As stated previously, Bowyer (2011) formulates this process as "wealth without money". This model differs from the capitalist mode of production where companies or factories manufacture the machines and sell them to the customers. However, the concept of self-replicating can become problematic for developers on the mailing list.

> Since RepRap as a project is not about making commercial products, quite the reverse, it is about creating self-replicating machines and thereby enabling each person to make their *own* 'products' locally (!), that weird license is not an obstacle to use in the replicating RepRap world, as far as I can see (ReRM14 from the mailing list).
>
> Part of me thinks that, as someone replicates their RepRap for a friend/neighbour, it would be good also to be able to hand to the new RepRapper a complete copy of all the software and documentation needed to build, use and modify it. So, we are not just replicating a hardware "product", we are replicating the whole system. Philosophically, to me, this makes sense (ReRM14 from the mailing list).

The claim of wealth without money is mainly based on the idea of self-replication. The machine that self-replicates enables people to build new 3D printers for others. This idea, that ordinary people can easily access the means of production, seems quite revolutionary. The manufacture and distribution of the machines theoretically require a solidarity network for the sharing of software, designs and hardware devices. If the network can be created, the means of production may escape the control of company-based production and technology cartels.

> RepRap is a self-replicating 3D printer. It is so versatile. It is capable of printing a large fraction of its own parts, so it is not only open source but also,

> to a certain extent, solves the problem of making copies of itself, and that's why I was really interested (Interview with ReRM05).
>
> It is wealth without money. I am a firm believer. I ideologically approve of this idea. We can have unlimited copies. We can create enough wealth for everyone on the planet through technological development, through moderation, through the conversation. I would say that is the direct motivation. Everything else stems from that (Interview with ReRM10).

Self-replication is a way to make "unlimited copies", and "create enough wealth for everyone on the planet". The claim of wealth for everyone follows a certain communitarian ideology because the developer aims to share the wealth created by self-replicating machines with others, rather than develop a new technology to sell. The self-replication aspect has the following advantages:

> The device and manufactured parts have to be capable of a certain level of fidelity/quality. 2) It is a design constraint that enforces simplicity. 3) It is possible to use your first machine to build a different one with different capabilities. 4) One maker can bootstrap others. 5) There is an asymmetry in that other printers can make RepRap but not vice versa. Thus RepRap will almost certainly win the network effects race (ReRM20 from the mailing list).

Even though the idea of self-replication is quite interesting and innovative for the production and distribution of technology, some RepRap developers think that self-replication should not be the main goal of the RepRap project.

> Self-replication is important to me, but I don't see that as the ultimate goal or priority goal… self-replication machines, in my opinion, is "bad" marketing and things like that fool new users… I hope to not criticise "self-replication" of RepRap. I do not agree with it because I am seeking to develop a quick and ease of usage of 3D printer, also DIY and cheap as possible. (ReRM04 from the mailing list).

Users do not have to buy new kits or machines from the companies that produce self-replicating machines. One of the developers, therefore, finds the self-replicating idea a terrible marketing strategy for his own goal, and he seeks to commercialise his own RepRap products. "One advantage 'I have' is that I will commercialize the hardware, that is one motivation… I believe that being able to produce and commercialize [hardware] will be a key success for me" (ReRM04 from the mailing list). This reflects an idea that uses the concepts of commercialisation or market, corresponding to a libertarian ideology oriented on the market value of goods.

Nonetheless, some developers strongly support the idea of self-replication for the RepRap project. "It [self-replication] IS ULTIMATE GOAL of THIS PROJECT" (ReRM02 from the mailing list), "100% replication is indeed the primary goal" (ReRM12 from the mailing list), "This is for the self-replication goal, not the cheap cost or quality

goals" (ReRM46 from the mailing list). Using capital letters shows how determined he is in his thinking.

One of the developers also claims that "RepRap does not need to do marketing or try to compete because it is not selling anything. It doesn't rely on sales to exist as companies do" (ReRM01 from the mailing list). This developer does not care for the commercialisation of RepRap and marketing of RepRap stuff. The concepts of market and competition are essential elements of the classic capitalist system. He also states that RepRap does not involve selling as companies do. This statement reflects an aspect of communitarian ideology more geared to the use value of goods. It is clear that there are conflicting views in the RepRap community regarding the RepRap goals. Some developers see the project as a new opportunity to develop technology in contradistinction to the companies-based production model. Self-replicating machines can play a vital role in the creation of wealth without money. Wealth, I argue, refers to use value, not exchange value in this context. Some hackers in the RepRap mailing list support the goal of a low cost, high-quality 3D printer.

> The real goal here is a generic low-cost 3D printer that can be built with a minimum of expensive parts that would have to be sourced externally to a third world economy (ReRM24 from the mailing list).
>
> Even though the core goal of RepRap is self-replication, I think that the goals of a high -quality printer and a low total cost RP based printer are perfectly within the goal of the project in the long-term (ReRM23 from the mailing list).

The concept of self-replicating is open to different interpretations for RepRap developers. Some developers can see in the self-replicating machine a significant opportunity for the creation of wealth without money for everyone, everywhere, while others might see it as an obstacle to a marketing or business strategy. For example, the OSS movement avoids calling its movement free software because the meaning of "free" is problematic for open source business. Similarly, the term "self-replicating" can be seen as problematic by some RepRap hackers in terms of the commercialisation of the RepRap project. Still, RepRap remains an important platform involving developers from different backgrounds. One of the developers asserts that "…RepRap is a big tent. Everybody fits under it. But keep in mind that not everybody has exactly the same goals or is doing it for exactly the same reasons" (ReRM21 from the mailing list). The concept of the tent here refers to a platform where hackers have different ideological backgrounds regarding the goal of community work. In an interview for *New Left Review* Richard Stallman states:

> Basically, free software combines capitalist, socialist and anarchist ideas. The capitalist part is: free software is something businesses can use and develop and sell. The socialist part is: we develop this knowledge, which becomes available to everyone and improves life for everyone. And the anarchist part: you can do what you like with it (Stallman, 2018).

Stallman categorises hackers in three groups in accordance with their political orientations. These groups come together under the "tent" of free software in which all groups become part of the production process of software. Ideological differences do not manifest in the production process. All groups follow the principles and ethics of a CBPP model, but hackers might have a variety of thoughts regarding the relationship between the commons and the market. In my opinion, the tent in this context refers to the commons, not the market, because "socialist" and "capitalist" cannot, ultimately, build a consensus with regard to the commercialisation of free software. In this research, I use the terms communitarian (for socialist and anarchist ideologies) and libertarian (for neo-liberal ideology) as ideological categories.

The libertarian hackers in the RepRap community have strong commercial motivations. However, as we have seen, the commercialisation of 3D printers based on RepRap can lead to the hyper-exploitation of productive fun labour of hackers. The RepRap community is a goal-oriented prosumer community, in which developers and volunteers develop a self-replicating machine to create wealth without money. Self-replication can be an important issue in the creation of a support network not based on the market. The idea of the self-replicating machine is a thrilling idea for communitarian hackers. It is also, I believe, a significant way to resist the hyper-exploitation taking place in the FOSHW communities. With the self-replicating machine, productive fun labour of volunteers in the community avoids exploitation by the companies selling 3D printers. The idea of self-replication has the revolutionary potential to liberate the means of production from the capitalist and to stop the exploitation of creativity of contributors; yet the libertarian insists on developing open source 3D printers with a market value. We see the contradiction between the communitarian and libertarian viewpoints.

3-The Issue of Customisation

Customisation: FOSHW is also known as a DIY movement that self-builds its machines or devices. The customizability of a product means users can adapt the product to their needs. In this way, the standardisation of production and manufacturing resulting from mass production can be prevented by desktop production enabling people to manufacture

at home. One developer observes, “The upside of this is that any machine we may currently refer to as ‘customised’ or ‘unusual’ or ‘special needs’ would just become a printer with a specific set of ‘features’ turned on” (ReRM08 from the mailing list). This can have implications for a culture based on mass production and consumerism.

> OSHW projects are often “faster time to get”, as a big part of them I can make myself; the usability is directly linked to customizability, and the open project you can customize and adapt to your need. No one can create a device, app, system that is a silver bullet and will fit *everyone's* needs, but if you can customize, you can take a project and make it fit your needs. On the other hand, if it is closed you usually cannot adopt it at all, and you are at the mercy of some designer and some engineer, and you must use the system the way they had in their mind that it should be used - but like we are not all same we do not do things in the same way either so being able to customize things is a huge potential (ReRM02 from the mailing list).

Closed source projects do not allow users to change or modify anything, and users have to stick to the policies of proprietary companies that give priority to making a profit from technological goods. Hackers, however, can have a different motivation in the development of technology. The ambition to access all sources of software and designs closely correlates with the ambition to customise technological products for hackers. In this sense, customisation is an important question for the free open source movement- both software and hardware- because it reflects some of the movement’s essential themes. For instance, freedom is probably the most significant principle for the free software movement, signifying freedom to modify, change and distribute software. Customisation in this respect can refer to control of technological products. One of the developers, nonetheless, points out that customisation can create a new marketing strategy that increases costs.

> Just pulling out random numbers, if 1% of consumer goods were produced by home / local flex manufacturing for a customer order, I would see that as a significant landscape change. That would be achievable with slower more expensive manufacturing because the customization would be worth a premium. (ReRM36 from the mailing list).

> And buildings, in particular, are a *great* application for one-off construction. IE, there's an existing market where people are willing to pay extra for customization (ReRM21 from the mailing list)

As stated in the previous chapter, desktop production can have the strong potential for domestic production and access to the means of production. Users can acquire great advantages through personal manufacturing tools such as the self-replicating 3D printer, and in the process weaken technology cartels that produce closed source products. The

idea of customisation can therefore be a little problematic for closed source companies if these companies are to insist on closed source policies, and not share software and designs with users; without the source code, no one can customise products in accordance with their needs. In this respect, customisation can be a marketing strategy for open source products alone. Customisation is therefore be considered a new marketing strategy by some developers in the RepRap community. Customisation has different meanings among the developers. On the one hand, one of the developers claims that customisation cannot co-exist with closed source policies, as it allows users to adapt the products to their needs. In this way, users of technology can sidestep the culture of consumerism and mass production because customisation obviates the standardisation of culture. On the other hand, some developers argue that customisation creates a new marketing opportunity with costs involved.

Customisability of FOSHW products enables hackers to boost their creativity as with self-replicating machines, in that people can adjust their machines to their needs. This is the freedom to change and modify hardware goods to suit the requirements. Customisation of RepRap produces differences and unstandardized products that uncontrolled by top-down management. Peers have manufactured a great, diverse range of RepRap machines around the world by customising RepRap designs according to their needs. In this way, innovation is getting faster since customisability allows hackers to be more creative in the development of RepRap.

4-The Issue of Intellectual Property Right Tools

License: One of the issues most discussed in the free open source movement for over three decades has been intellectual property rights. The license is one of the most popular tools for intangible goods and software; it aims primarily to restrict the flow of information to protect copyright holder' rights. As stated previously, the term license means the legal way a copyright and patent owner grants permission to others to use his intellectual property" (Rosen, 2004, p.52). However, the free open source movement applies copyleft licenses or open source licenses to keep all sources open. The concept of license, therefore, can have different meanings for RepRap developers.

> I have thought about this before. What would be really cool is if an organization like the EFF, Creative Commons, GNU, or some partnership among them formed a patent pool to file "Open patents." These patents would be just like normal patents but would be released under an open source license with a share-alike clause so that they can be used by anyone freely, but only

> for open source projects. They have to open-source their designs… (ReRM07 from the mailing list).

> I am developing an invention meant to be *fully-opened* as RepRap or Arduino, and I was thinking to protect this work from being closed in the future, exactly in the same way... putting everything on a website under cc license (ReRM67 from the mailing list).

For some developers, copyleft or creative commons (CC) licenses are tools that protect free open source products from being closed source in the future. License, therefore, refers to a protection law that enables hackers to release and share their FOSHW projects freely, preventing conversion of FOSHW products into closed source products. For these developers, commercial companies can use free open source products for their own ends, but they have to keep all source of products open to everyone. So, licenses might serve to protect and benefit the commons or public domain, as opposed to serving the interests of technological cartels. Lawrence Rosen (2004, p.52) asserts that "an open source license is the way a copyright and patent owner grants permission to others to use his intellectual property in such a way that software freedom is protected for all". Even though the aims of copyleft or open source licenses are entirely different from those of corporations producing closed source items, one of the developers in the RepRap mailing list rejects all kinds of license, even copyleft, in his work.

> I do not care about the law, and I do not care about patents, licences, etc... I ignore any type of authority; I do not recognize it ... so it does not influence what/how I do stuff. Look at small kids that are not yet tainted with the modern concept of the "law and order" they quickly learn to share on their own, and the more they share, the others share with them... There are always kids that "do not want to share" and try to "take by force" (when others are not ready to share) and those kids quickly get excommunicated by the group.... so sharing is a natural state of things. Involving authority, law, patents, licences. It only spoils the whole thing (Interview with ReRM02).

According to this developer, the license is a type of authority that poisons the nature of things based on sharing. The developer is not just against licenses serving closed source companies, but also against copyleft licenses. "There will always be someone trying to push some bullshit philosophy over it [open source] with licences and all that jazz (like Stallman is doing for GPL) the activism on "everyone has to share" etc." (Interview with ReRM02). He denigrates copyleft licenses and fails to see it as a useful tool for FOSS or FOSHW, as he believes that humanity already has a sharing nature. This is a type of a political idea pertaining to anarchist ideology that rejects all kind of authority and supports sharing, communitarian activities.

Copyleft-type licenses generally allow users to use free open source products for commercial purposes. Some of the developers are disappointed with the use of their free open source products for commercial purposes and attempt to apply a new non-commercial CC license for their products, instead of GPL.

> If someone develops a design that is a complete, superior product on the market, that a commercial vendor can ship directly without modification and fully satisfy their customers, they have no need to license the GPL design ... they are free to ship the GPL design without modification, without a fee (ReRM24 from the mailing list).
> NC licenses are an indicator that the community has a problem. For me, the ideal situation would be a community where everybody works together. People help each other with ideas, support and if there is money coming in it is spent on the needs of the community and the rest is given to those who need it (ReRM34 from the mailing list).

As previously mentioned, the free open source movement is not against making money from free open source products, but some developers in the RepRap mailing list are not happy that commercial vendors use their products for commercial purposes without paying a fee. This represents exploitation for hackers because free open source products are outputs of hackers' labour. Developers are unhappy about the exploitation of their labour by commercial vendors. There exist no mechanisms to organise the fair-sharing of money in the community. A non-commercial (NC) license, therefore, can be seen as an alternative in preventing the exploitation of developers' labour.

However, one of the developers is against the NC license. "NC licenses are just patents in a weak form… They both limit other people to be creative, and they frustrate them. People will avoid your idea and do other things instead. In other words, they put an end to innovation" (ReRM73 from the mailing list). Non-commercial CC licenses mean "not primarily intended for or directed towards commercial advantage or monetary compensation" (Creativecommons.org, 2017). It is claimed that the NC license does not cover free software or open source principles. There is an incompatibility between NC licenses and open source licenses. The NC license is free-to-download, educational, maker-friendly, transparent and hackable, but it is not open source (Muirhead, 2015). Although the NC license allows people to share, distribute and modify products, non-commercialism can be seen as an obstacle killing creativity and innovation because commercial activities are accepted as a premise of creativity and innovation. The idea of commercialisation is supported by a libertarian ideology in which the market is the key player in the innovation and development of technology.

As I said before, the license is used as a bridge between the creative works of hackers and intellectual property. Some hackers, in particular libertarian ones, support the license that allows them to commercialise open source products. They do not accept the NC license as an open source license, as this license does not allow them to profit from the products developed by the community or anybody else. The NC license enables users to use, change and modify FOSHW design and software for their needs; this license just restrains commercial drive in order to prevent the hyper-exploitation of productive fun labour of hackers. In other words, the NC license is different from open and copyleft licenses allowing developers and companies to build a bridge between intellectual works and intellectual property.

> I'm considering Creative Commons Non-Commercial licensing as a balance, which will certainly raise the hair on some of the free "as in beer" folks. Supporting this with BSD-ish licensed material and projects is relatively easy, doing this with GPL licensed material and projects is near impossible…The balance is that my work is open, and it's a clear statement those stealing it for a profit (or to subvert into GPL) are ass-holes (RepRap12 from the mailing list)

> I personally do not want reputation for designing, building, and shipping inferior products under GPL, with some hope that a vendor will multi-license the really good version of the design in exchange for commercial rights. I do not see any way to ship a really good open design without CC non-commercial licenses when I need to hold established competitors in the market off so I can get paid for the many hours and dollars in the R&D (RepRap11 from the mailing list)

Hackers can sell open source products under open source, copyleft and some CC licenses. As stated before, property means the right to distribute products in open source communities, but the property is also the right to exclude digital goods under the management of proprietary companies (Weber, 2004). However, closed source-based licenses allow proprietary companies to profit from the products developed by their companies, while open and copyleft licenses enable hackers and companies to make money from FOSHW. Libertarian hackers, therefore, do not support the projects protected by the NC license, and they consider this license to be damaging to open source policies. However, the NC license, I believe, can be an effective tool preventing companies from exploiting the creativity of volunteers.

Patent: Patents represent another tool of intellectual property rights as discussed on the mailing list. As I mentioned in Chapter 4, hackers do not usually apply for patents to protect their inventions, given that the application for a patent is costly and time-

consuming. Some developers, nonetheless, propose the creation of an open patent model for RepRap projects.

> What would be really cool is if an organization like the EFF, Creative Commons, GNU, or some partnership among them formed a patent pool to file "Open patents". These patents would be just like normal patents but would be released under an open source license with a share alike clause so that they can be used by anyone freely, but only for open source projects. If commercial companies want to use them, they have to open-source their designs and license the other patents used in it the same way (ReRM07 from the mailing list).

The possibility of commercialisation of RepRap 3D printers by proprietary companies causes dissatisfaction in the community because hackers do not want these companies to use the products they designed and developed for commercial purposes. Some RepRap creators therefore suggest an open source patent model for hackers to protect their inventions from the companies; but another developer in the community gives some information regarding the cost of application for a patent: "A German patent will be about 15,000 EUR if all goes well. A patent valid in more countries (say 9 European countries) will cost at least 60,000 EUR. There is no such thing as a worldwide patent." (ReRM65). It is also argued that patents are not suited to the principles of the free open source movement:

> Open source and patent law don't mix... If Adrian wanted to patent everything to protect it from commercial interest, then he would not have made it open source…I don't seem to remember there being anything in the RepRap goal about keeping the IP open for individuals, but for non-commercial usage. RepRap even encourages people to start selling/giving parts to others in the community to make the idea spread...for world domination (ReRM49 from the mailing list).

The discussions on patents and non-commercial licenses on the mailing list essentially result from the tension between the commons and the market. Patents are considered to be an instrument of legal protection shifting the commercialisation of RepRap 3D printers in favour of hackers, instead of proprietary companies. However, some developers believe that the restrictions on marketing of RepRap can damage the flow of ideas, so patent and NC license, in this respect, do not serve the principles of open source. The communitarian and libertarian ideologies are in conflict at this point.

5-Fun in the RepRap Community

Fun: One of the main motivations of hackers in free open source communities is fun. David Graeber (2014) asserts that "having fun, doing something we do well for the sheer pleasure of doing it". However, as said before, fun for hackers does not mean playing the game Counter-Strike; it refers to doing something cleverly or overcoming challenges during the production of technology. Creative efforts are the central element of fun or hobby for hackers. Voluntary labour is a dynamo in free open source production; most hackers are not motivated to make money from free open source products. Voluntary labour is therefore intrinsically linked to hobby or fun activities. "Hardware is a hobby for me. When you do it for money, it stops being a hobby and becomes being a job. I already have a job; this is a hobby so no money" (Interview with ReRM02). He also adds

> I do electronics and robotics for fun, talking shop takes all the fun out of it... You don't want to do electronics for fun; you want to make money - your viewpoint is different than mine for a start because we have different goals. I use RepRap project to have fun, satisfy need to make something that works that I can touch (as I'm sick of doing all the virtual stuff for the past few decades). I spend a lot of money on RepRap and stuff around RepRap (I spend on it monthly more than the average salary in my country), but I do it to make myself happy, not to make money in future (ReRM02 from the mailing list).

Having fun or pursuing a hobby, in my opinion, are activities hiding the voluntary labour of hackers in the FOSHW movement. Therefore, I call this labour "productive fun labour". There is no strict line between leisure time and work time or fun and labour. One of the members of the RepRap community asserts that having fun or a hobby should be with unpaid work. If you make money from free open source projects, it is a job, not a hobby. Volunteers in the RepRap community contribute the project in their free time and they are unpaid. However, the RepRap design has created significant value in the market with the MakerBot company (Moritz et al, 2018). This value is mostly based on the exploitation of creativity and free time of peers (Kostakis and Bauwens, 2014; Harvey, 2017). Productive fun labour might provide peer production with excellent opportunities for sharing activities, reducing the costs of products, acquiring skills and so on. However, there is no consensus on the RepRap mailing list regarding the making of money from productive fun labour.

> Why would it bug me if someone is making money off work I did for fun?! It will only make it more fun?! If I invested money trying to earn money and then someone is taking "piece of the cake I intended to eat" from me - then I'd be frustrated but if I did it for fun and someone can use it to make money

> - cool, let them. It will make my work more pleasurable (ReRM02 from the mailing list).

For this developer, it does not matter if someone makes money from his fun labour. He also asserts that making money from his products makes his work more pleasurable. Another developer disagrees.

> Even if you develop for fun, it's often no fun to see somebody else just to grab the result of all the hard work and make money with it. To some extent, money is a reward for good work, and to that extent, it belongs to the developer (ReRM03 from the mailing list).

> As we all know, the chance to make a profit is one of the driving factors of the RepRap community. There is nothing bad about this. So far, this chance is pretty much limited to those running a shop, though, whether they contribute or not. Accordingly, development is limited to shop owners and hobbyist volunteers, the latter working just for the fun of doing it. And there is kind of a dis-balance between those giving and those just taking (ReRM03 from the mailing list).

The exploitation of fun labour is one of the vulnerable areas of FOSHW production. Some developers do not care less the exploitation of their labour than the development of technology. Furthermore, these developers see the activities in the RepRap community as free time activities that remain unpaid. Other developers still are unhappy with the exploitation of productive fun labour. Hackers enjoy what they do for RepRap projects, but making money from voluntary labour is seen by some as exploitation; developers can legitimately be unhappy with this. One can see the concept of fun as a mask hiding the exploitation process in free open source production. In general, hackers see the technical development of RepRap as the fun stuff.

> I'm not really sure if we'll reach any great consensus on nomenclature matters from discussing them at length, and I don't know if it's a good use of dev-time, as it may drift into “philosophy” and delay the development of any and all boards, including the fun stuff Chris is doing up (RepRap13 from the mailing list).
> Helping design a better Mendel, a better post-Mendel, or a better RepStrap is much more fun than just arguing about it. We could continue on with philosophy, but it's not as much fun as development (RepRap13 from the mailing list).

It is important to note that fun stuff refers to the activities of FOSHW production. As said before, if the outputs of this production can turn into money, and producers mostly do not receive wages or make a living from it, it represents the “hyper-exploitation of producers” (Harvey, 2017). At least workers can obtain salaries within the capitalist mode of production, but there are usually no wages in peer production (Ritzer, 2014). Free open

source production, therefore, might be open to manipulation by those who seek to use it to make a profit. Productive fun labour is an important issue in contemporary capitalism. This labour on the one hand can be used in the development of FOSHW projects for the benefit of society by providing users with cheap or free design and software. On the other hand, it is possible that the companies exploit productive fun labour of hackers in favour of capitalists.

6- The Structure of the Organisation

Every community must have a structure enabling people to unite around a goal. The community mostly consists of a range of people with different backgrounds. The structure of the community illustrates how people work together and communicate with each other. The structure also shows the social positions of people and how power is exercised in the community. The RepRap community organisation is much more horizontal than vertical:

> We do not really have any rules about what license you use or any rules about whether a given design is good for RepRap or bad for RepRap. If people disagree about something, Person A and person B do not agree. I say well, person A you go away and do your idea, person B you go away and do your idea and the world will see which one is better because the better one will probably become more popular so it's a Darwinian process, and that is it (Interview with ReRM05).

Here the Darwinian process is based on decentralised network platforms where developers create a network to enhance collaboration or announce the projects they have developed. In the Darwinian process, individuals exercise strong autonomy in the development of the RepRap machine. However, some developers argue that there is no organisation in the community:

> Regarding organisation, I can only talk about the RepRap community. And there is no organisation. It's a forum and a wiki running headless… There is no direction given, no goals to achieve are laid out, no inspiring vision of the future. Some people tried to set up such goals, but nobody followed. Community founder got mostly inactive years ago, just answers or forwards emails directed to him (Interview with ReRM03).

The RepRap community is described here as a leaderless community where a leader does not encourage or inspire the developers to innovate. This developer probably believes that without a strong leader and organisation, the community does not function properly. However, RepRap is not a community with such strong leadership. The community has a natural leader and is under his management:

> Adrian [Bowyer] is the guy that really made it [RepRap] his life, who is universal. In my opinion, he is universally respected (Interview with ReRM09 from the mailing list).
> Even though the hierarchy was there, it was very shallow. It was very quick to traverse so you can show up and you have a patch that did something interesting. Whether or not people wanted it, you were basically in and that was a part of Adrian's management style (Interview with ReRM10).

Bowyer seems "a benevolent dictator" in this context. As previously discussed, the benevolent dictatorship is a popular management style in the FOSS movement (Bauwens, 2009). For example, the Linux Kernel project is under the management of Linus Torvalds, a benevolent dictator with in-depth technical knowledge of project, diplomacy and community building skills (Gardler and Hanganu, 2010). The Debian Project seems a more democratic management type based on a voting system (Debian.org, 2018) However, Bowyer as natural leader of the community, does not impose his decisions on other hackers; instead, he allows hackers with different ideas to develop their machines. One of the developers states that "RepRap doesn't actually do consensus. We tend to explore both parts of every fork, which is fun" (RepRap 06 from the mailing list). As I said before, hackers in open source communities choose, rather than being allocated a task (Berdou, 2010).

> Firstly, RepRap-dev is a collective of people, and not a 'team'. There isn't that sort of cohesion in a group like this. Secondly, if you've ever worked with open source style projects before you should know that getting anyone to stay on a charter is a bit like herding cats. People work on what they want to work on. You can sometimes convince them to work on other stuff, but you need a good argument, or convince them to work on it in parts, by championing short term goals that lead in the direction you want (RepRap06 from the mailing list).

> Some people work well in a group, some people work well alone – you cannot force one to behave as another, especially if they work for free, in their own time, on their own project?! No-one said it is insensitive to support it, what happens here is that it is being forced! It is a huge difference! You can't force people to think what you think nor to behave how you think they should (RepRap02 from the mailing list).

There is no good or bad idea for the RepRap project under the management of Bowyer. In this sense, democracy or consensus does not exist in the community because according to Bowyer, the superior project will naturally be more popular and endorsed by the community. There may be no classic hierarchy or vertical organisation in the community, but there is a new type of hierarchy based on the strength of community members' engagement.

> Some people only contribute to one idea and go away, but it might be a good one. The community is not formally hierarchical in any sense at all, but there are people who are very active in the community… they are very active; they tend to get a lot of respect in the community, so the community generates a hierarchy in that way, but it's not in any form or acknowledged it. It's just the way things happen to self-organise (Interview with ReRM05).

As stated in Chapter 4, hackers strive for a good reputation in the free open source movement through their contributions to free open source projects, and this facilitates hackers in their pursuit of paid work. For this reason, hackers try to be more active than other community members. This competition leads to a different level of participation for hackers, and hackers or developers acquire status in the community, from the most active to the least active. As I said in Chapter 1, the most active contributors in open source communities are core-developers at centre of the community while the least active ones are volunteers at the periphery (Berdou, 2010).

7-Collaboration in the RepRap Community

The RepRap community has several communication tools such as mailing lists, forums, and social media accounts allowing users and developers to communicate and collaborate with each other. There are plenty of communication and collaboration tools used by the contributors of the community. Even though traditional mass communication tools are used to announce innovations, radio, television, and newspapers do not play an important role in the communication process between RepRap users or contributors. The internet is the primary communication and collaboration platform.

> Email lists were the most common thing. Forums like buildlog.net IRC is still around, and more recently Slack has been popular (Interview with ReRM26).

> I read the documentation and use e-mail addresses. Twitter is good and gets responses from other followers of a person or project. Participating in GitHub works well as it helps collates issues and brings developers together. (Interview with ReRM06).

> Sharing happens through a plenitude of public channels, like forums, mailing lists, blog pages. As appropriate, files are uploaded somewhere, e.g. to Thingiverse or GitHub. (Interview with ReRM03).

> I use GitHub, Sourceforge, forums, google groups, mailing lists... when one has a problem one talks about the problem, when others want to help, they offer, communication and collaboration tools are all around us, from Facebook to Skype it is very easy to reach out and talk to ppl (Interview with ReRM02).

FOSHW projects are usually shared on thingiverse.com, a website used for the sharing of 3D printer designs. The designs shared on this website are mostly FOSHW designs and are licensed under GPL and CC. Github.com is another website dedicated to the sharing of FOSS under GPL, CC and open source licenses. Designs and software of RepRap 3D printers are distributed on these websites at almost zero cost, but the RepRap community, including users, contributors, developers, and designers is the centre of software production and self-replicating machine design.

The RepRap community draws on its mailing lists, forums and blog pages in the development of design and software. RepRap developers and users visit the websites and blog pages of open source and proprietary hardware projects, to stay informed about the latest innovations. The developers participate in numerous mailing lists and forums other than those of the RepRap community. The RepRap users and hackers also use social media platforms, proprietary companies such as Facebook, Twitter or YouTube that make huge profits from the commodification of users' personal information amongst others. In this sense, the RepRap supporters can apply for closed source communication tools as long as these tools allow them to contact people with the same interests. RepRap becomes a community following the principles of the free open source movement, but the members of the community are pragmatic in their use of social networking tools, namely proprietary companies Facebook, Twitter, and Skype. The internet also allows hackers to seek and find funding. One of the interviews asserts that "projects asking for funding are often found on fundraising sites like Kickstarter or Indiegogo.[51] These platforms also serve well for initial advertising, along with pointers to it in other communication channels" (Interview with ReRM03). As has been previously stated, hackers require sufficient money to manage the prototyping or manufacture of open source hardware projects. Fundraising sites can be an excellent platform to obtain funding for turning a design into hardware goods. These sites act as a type of communication channel where inventors can inform their funders about their inventions.

I have shown in the ideological struggle between developers on the RepRap mailing list that hackers may have different ideologies, rooted in what might be termed "communitarian" and "libertarian" wings. This debate often takes place as an ideological struggle between RepRap developers, a phenomenon I have uncovered using thematic analysis. In the analysis of the key themes of: "the issue of open source", "the issue of

[51] Kickstarter or Indiegogo is a commercial website.

self-replicating", "the issue of customisation", "the issue of intellectual property right tools" and "fun in the RepRap community", I have shown that there is a constant tension between the commons and the market on the RepRap mailing list. Hackers attribute meaning to key concepts according to the ideologies they support. I argue that there are two main ideologies supported by developers: the communitarian wing that is generally supportive of the idea of a commons, in which the free circulation of ideas and creative collaboration take place in communities, and the libertarian wing that is usually more supportive of the market. Communitarians often support the idea of self-replication and mostly reject the collaborative relationship with proprietary companies while the libertarian hackers usually do not see the exploitation of the creativity of volunteers and developers by companies as a threat. Libertarians constitute a sort of mediating group that seeks a way to reduce the tension between straight dominance of companies and pure creative forces of open source communities. The RepRap community has a leadership that allows hackers to develop their machines yet provides ideological leadership in debates and questions over future directions. However, developers have strong autonomy under the management of Adrian Bowyer.

Note, however, that the community is male-dominated, made up of highly skilled and experienced hackers and developers, and this can result in a particular worldview which can go unchallenged within the community as it stands. RepRappers mostly use GitHub, Thingiverse, forums, mailing lists and social media to communicate and collaborate. In the next chapter, I build on this analysis in greater detail.

Chapter 6: Arduino as a Free Open Source Hardware Project

This chapter examines some pertinent issues in FOSHW communities by looking empirically at the case of the Arduino community. In the first part of the chapter, some details are given regarding the background of the Arduino community in data taken from the Arduino website: Arduino.cc, and the articles written by the leaders of the community. The second part includes corpus analysis and thematic analysis of the Arduino community drawing on data from the interviews and developers' mailing list archive. The primary sources will be analysed using these techniques (corpus, and thematic) to decipher the power relations in the community and acquire a deeper understanding of FOSHW culture.

Background to Arduino

Arduino is a FOSHW platform where electronic, easy-to-use microcontroller boards are produced. The board allows hackers to create new electronic devices for desktop manufacturing. It is essentially working with a mechanism reading inputs and turning them into outputs. In this way, users can give a set of instructions to microcontrollers on the board regarding what to do. The boards have been the brain-centre of many projects, from simple devices used in everyday life to complex research objects (Arduino.cc, 2018a).

Arduino is also a free open source hardware community consisting of hackers, makers, hobbyists, artists, developers, and professionals. One of the main motivations of the community is to create a platform where knowledge is accessible to all through the contributions of community members. The fact of the project being free open source and user-friendly enables makers to build new electronic devices at home according to their needs. Reducing the costs of microcontrollers and boards is another motivation of the Arduino community. Fundamentally, Arduino intends to create a board which is an "inexpensive, cross-platform, simple and clear programming environment, open source and extensible software as well as hardware" (Arduino.cc, 2018a)

Arduino was founded by Massimo Banzi, David Cuartielles, Tom Igoe, Gianluca Martino, and David Mellis in 2005 in Italy. The project, based on the works of Casey Reas, Ben Fry, and Hernando Barragon (who wrote a thesis on the Wiring board), was developed at the Ivrea Interaction Design Institute (see Barragan, 2016). The first Arduino board was launched in 2005 to help non-engineers in the field of microcontroller programming and electronics to create working prototypes that connect the physical to

the digital world. Since 2005, the Arduino board has become the most common electronics prototyping tool used by hackers and makers. Arduino simplifies the process of working with microcontrollers. In this way, many amateurs lacking in-depth information on electronics- such as students, hobbyists, and makers- do not have to deal with the complex details of microcontroller programming (Arduino.cc, 2018b).

In 2008, the Arduino company (LLC) was incorporated in the USA. It led to the Arduino community, producers of Arduino software and designs (Williams, 2015). The company applied for a trademark for the Arduino name and logo in 2009 to manage the business of the project in the USA, and the application was granted in 2011 (Willis, 2015). On account of this legal protection, manufacturers using the Arduino name and logo on their products were obliged to make a royalty payment to the company. However, in 2010, there was a significant dispute among the founders on the question of the Arduino company's intellectual property rights. One of the co-founders of Arduino, Martino, had applied for a trademark (Smart Projects, (SRL)) for his company in Italy in 2008, without advance warning to his colleagues. Other co-founders, Banzi, Cuartielles, Mellis and Igoe noticed that the registration of the Arduino name for a trademark had already been placed two years previously in 2010, when they tried to apply for a trademark in Italy (Banzi, 2015). Although they registered the Arduino name and logo as a trademark in the USA in 2008, Martino was the Arduino trademark holder in Italy and Switzerland. The crisis arising from the disputed control of the trademark eventually caused a split in the Arduino community. By 2017, there had been two companies holding the Arduino trademark: Arduino SRL, (Smart company changed its name to Arduino SRL in 2014) arduino.org in Italy and Arduino LLC, arduino.cc in the US (Williams, 2015).

The battle between Arduino SRL and Arduino LLC over the trademark "Arduino" deeply divided the Arduino community. This split was clearly a disappointing event for those who had become part of the Arduino community and supported the FOSHW movement. It is important to note that the battle in the community did not result from a disagreement over the production model of open source hardware but instead from the disputed control of the trademark. At the beginning of the 2010s, two different companies were using the Arduino name and logo; this caused serious confusion in the hacker movement (Allan, 2015). In 2014, Federico Musto took over the management of Smart Projects from Martino and renamed the company Arduino SRL. One of Musto's most interesting projects was to create a non-profit Arduino foundation. This was significant because the FOSHW movement was mostly based on the voluntary labour of hackers.

> [Musto] told us that he envisions an "Arduino Foundation" with clear and open balance sheets and a democratic governance structure. Think Mozilla Foundation mashed-up with Debian's governance. The Foundation would be open to all stakeholders in the Arduino community. [Musto] said that he's currently in the middle of paperwork and that there will probably be announcements forthcoming. We discussed how such a foundation could also be used to funnel some money back to the Arduino community because after all a lot of the success of Arduino is due to the code contributions of users (Williams, 2015).

In spite of Musto declaring that he wanted to create a foundation for the Arduino community, he still had a poor reputation in the hacker movement because he had fabricated his academic record. Musto claimed that he held a PhD degree from MIT on his personal LinkedIn accounts and on Italian documents, but the university could not find any record of his attendance. At the end of the day, Musto was forced to admit that he did not have a PhD (Biggs, 2017; Stockton, 2017). Following the scandal some open source hardware supporters argued that Musto was not trustworthy enough to lead the Arduino company or foundation:

> It is bothersome that Federico Musto is acting as the spokesman for the Foundation. This is the same Musto who admits that he fabricated his advanced degrees from NYU and MIT. Whatever the legal or business reasons why Musto ended up with majority control over Arduino, there is no justification to have him in control of the foundation. Musto has shown us that he cannot be trusted. It is bad enough that he has gained control of Arduino Holding. We must not allow him to control the foundation (Dougherty, 2017).

In 2017, two companies, Arduino SRL, and Arduino LLC declared that Arduino was to become one company, called Arduino AG, with a settlement agreement. According to this agreement, Musto would control 50%, Banzi and the other three co-founders Mellis, Cuartielles, Igoe (BMCI) 49%, with Martino owning just 1% of the company (Stockton, 2017). The leaders of the company also declared that they would form a separate not-for-profit "Arduino Foundation" to continue the production of Arduino boards, maintain the free open source movement, promote developers' initiatives and offer scholarships to hackers and researchers (Moody, 2016; Arduino.cc, 2016). Musto appeared to be in an advantageous position with this agreement on Arduino AG, but he sold his shares to BMCI and agreed to step aside. BMCI announced that it had acquired 100 % ownership of Arduino AG. Banzi became the new chairman and chief technical officer (CTO) of Arduino AG, and Fabio Violante was declared as the new chief executive officer (CEO) (Audioexpress.com, 2017). This was a pivotal moment in the history of Arduino:

> This is the beginning of a new era for Arduino in which we will strengthen and renew our commitment to open source hardware and software, while in parallel setting the company on a sound financial course of sustainable growth. Our vision remains to continue to enable anybody to innovate with electronics for a long time to come (Banzi, 2017)

> We envision a future in which Arduino will apply its winning recipe to democratise the Internet of Things for individuals, educators, professionals, and businesses (Violante, 2017)

When Banzi and his friends took over Arduino AG, hopes grew among hackers and hobbyists over the future of Arduino and the FOSHW movement (see Davis, 2017). Banzi's statement on the Arduino Foundation in particular struck a chord with those who supported the principles of free open source and democratisation of the internet of things (IoT). Banzi said: "The Arduino Foundation will allow us to champion the core values of the Arduino Community within the open source ecosystem and to make our commitment to open source stronger than ever" (Banzi, quoted in Stanton, 2016). Dale Dougherty, the author of Make, put forward some proposals for the Arduino Foundation:

> The Arduino team and Arduino Holding need to show us that the Arduino Foundation has been formed as an independent and open organization. The Arduino Foundation must
>
> - define its mission to protect and promote the interests of the Arduino community;
> - determine a board of independent directors who are not chosen by Arduino Holding; are not limited to the existing Arduino team; and excludes Federico Musto.
> - operate in an open and transparent manner.
> - Have visibility into the business of Arduino Holdings to hold it accountable as a watchdog (Dougherty, 2017).

It was clear that Arduino supporters were demanding a more democratic Arduino community wherein they could play an active role in the decision-making process. The community members were not happy with the process headed by the Arduino company or team. Broadly speaking, the Arduino Foundation could be described as an organisation that protected the rights of all contributors of the community and the principles of the free open source movement. Banzi announced that the Arduino Foundation would be founded in 2016, but the foundation is still not active in 2019.

Before June 2017, I completed the data gathering process with the interviews and Arduino LLC mailing list archive. LLC carried a lot more weight with the hacker and maker movements, as it oversaw a wide range of microcontrollers and a bigger community. The community of Arduino LLC, therefore, was selected as an empirical case for my research. In 2017, the team of Arduino LLC took over the management of Arduino

AG and became the sole legitimate and lawful leaders of the Arduino company. Choosing the mailing list archive of Arduino LLC (Arduino.cc) for the data collection in this research proved to be correct because Banzi and his friends have been the real leaders of the community from its early years.

The split among the co-founders of Arduino is based primarily on the difference of opinion over the Arduino trademark. A trademark means "a design, symbol, word or phrase that identifies the source of your products and distinguishes them from the products of other companies" (Haskins, 2015). A trademark is essentially a tool of intellectual property rights that protects the commercial interest of companies. The FOSS or FOSHW movement usually benefits from copyleft licenses to protect free open source projects from becoming closed source products. The Arduino community utilises GPL, open licenses, and CC licenses for the products of the community. However, Arduino as a company does not allow users to utilise its trademarked products, from software and designs to knowledge, for commercial purposes.

> Should the Site allow the downloading of specific contents, it is possible to download a copy of same to just one computer for exclusively personal domestic and not commercial use, subject to the condition that the user (a) does not remove or alter ownership or copyright notices in the downloaded content, (b) does not sell or modify this content, does not reproduce, view, publicly use, distribute or utilise same in any other manner for public or commercial purposes without our prior written authorisation, (c) does not use what he or she downloads in such a manner as to suggest any association with our products, services or trademarks. Without our prior written authorisation, it is prohibited to copy (being known as "mirror") any Site contents to any other server (Arduino.cc, 2018c).

The organisation of Arduino is based on both the community and the company. The commercial side of Arduino is the key part of the project for the founders. In this respect, it can be said that making money is one of the main motivations of the founders of Arduino. The leaders of Arduino, therefore, do not let manufacturers sell Arduino products with the Arduino name or trademark, but users and manufacturers can benefit from the Arduino designs and software to manufacture the microcontrollers for their needs without the trademark. For example, RepRap does not have a trademark and mostly uses GPL allowing users to change, modify or sell their products because the RepRap community is not based on just a company, and making money is not one of the main motivations of the leaders of RepRap.

The hackers make significant contributions to the Arduino community, in which production is performed following free open source principles. The members of the

community are part of the production process of Arduino boards. However, the main principles of Arduino are decided by the founders of the company, and these founders are eligible for a royalty payment from anyone who applies for the Arduino name or trademark on the products developed by the Arduino community. This can pose problems when it comes to the democratisation of technology, as Arduino has community-based production, and thousands of hackers, makers, and hobbyists are essentially producers of Arduino projects. However, a small number of professionals can, as owners of the company, play a determining role in the decision-making on Arduino's future, and make a profit from Arduino projects. Voluntary labour provided by the members of the Arduino community can thereby be turned into profit, with a royalty fee taken by the Arduino company. That is, unless someone applies a license covering his or her contributions. This comes back to the question of hyper-exploitation of the productive fun labour of community members (Kostakis and Bauwens, 2014; Harvey, 2017) As has been stated above, Arduino contributors have subsequently demanded that a foundation be created for the Arduino community, so that they can become involved in the decision-making process.

It was somewhat surprising that Martino claimed that Banzi and other founders tried to maintain the Arduino company as a non-profit organisation when the trademark crisis occurred among the founders (Banzi, 2015). Nonetheless, the Arduino company run by Banzi and colleagues has been highly profitable and has now became one of the most successful open source hardware companies in the world. Today, the rules and principles of Arduino are clear enough and determined by the founders of the company. There are, for this reason, no longer any serious discussions regarding the roadmap of the Arduino community.[52]

The Arduino community is ruled by the agreement on the Arduino website, which includes the principles regarding the terms of use of service in the community.

> Arduino cc ("Site") and the Arduino apps ("APP") are a Platform devised and managed by Arduino S.r.l. ("Arduino") which allows Users to take part in the discussions on the Arduino forum, on Arduino User Group and on Arduino blog, to access to the Arduino Playground services, to Arduino Day, to Arduino Create and CTC, to release works within the Contributor License Agreement program and to make donations for the purpose of further developing the open source Arduino ("Platform"). The use of the Platform

[52] Therefore, the data coming from the Arduino mailing list is not as rich as that of the RepRap mailing list in terms of qualitative data to analyse.

> and the use of the Services are governed by this Agreement in addition to the other policies published on the Platform (Arduino.cc, 2018c).

With this passage within the agreement, we understand that the Arduino community is based on the forum, mailing list and users' groups. The agreement explains how users act in the community, and how hobbyists become part of the production process of Arduino boards and sharing activities. With this agreement, the Arduino company expects that users obey the rules of the community and respect the terms of the license. Interestingly, to access some of the services on the Arduino website, users must make a payment to the company.

> In order to use some of the Platform functionalities, it is necessary to create an Account and to purchase a service available for a charge ("Premium Services"). Premium Services are products that the User can Purchase on the online shop of Arduino and have certain specifics indicated on the on-line when the purchase is made (Arduino.cc, 2018c).

It seems bizarre that there should be a "premium service" payment in an open source community, because, as stated in Chapter 3, one of the principal pillars of hacker ethics is to facilitate the free flow of information and knowledge. The implementation of such a premium service in the Arduino community can cause the classification of users into different groups who may or may not have access to the premium service. The users who do not have this service do not gain access to some of the services and information on the website. Furthermore, the Arduino company has the final say over users' acts and works.

> The user states that he or she has no objection as to publication, use, modification, deletion and usage of the Content by Arduino or its successors and assignees and the User states that he or she permanently waives all complaints or claims in respect of the Content (Arduino.cc, 2018b).

There is an asymmetric relationship between users and the company in the community, when users do not have access to premium service and have limited access to the sources of the community, and when the company has full power over users' activities. The agreement also contains some policies about the content shared by users on the Arduino website.

> The user has sole liability for the Content published or sent to Arduino or published on the Platform and undertakes not to publish, upload or otherwise make public through the Platform Content which: is false, illegal, misleading, defamatory, slanderous, intimidating, offensive or in any other way contrary to law and public morality… (Arduino.cc, 2018c).

Arduino is a practice of community where thousands of creators produce the goods for Arduino. The rules might be required for productive working conditions in the community. They should, however, also protect the interests of all people in the

community, rather than hand control of the community to the founders of the company. Accordingly, the Arduino Foundation can be used as a highly effective instrument to make the further strengthen core values of the Arduino community and open source principles. The foundation, like the FSF, would be a non-profit organisation deciding the basic tenets of the community. Musto, before stepping aside, brought forward an idea on the relationship between the Arduino company and the Arduino foundation: “Musto is considering having Arduino AG donate to the foundation in proportion to Arduino sales, and allowing the purchasers to earmark their portion of the donation toward a specific project as a form of radical democracy” (Williams, 2017). The foundation can be used as a platform to transfer money from the company, controlled by a small number of founders, to the community, which includes numerous developers, designers, and hobbyists.

Arduino boards allow users to build electronics devices in accordance with their needs. The devices can be useful either for scientific research or medical purposes or adapted to be a weapon or tool used to harm people or the environment. The foundation, therefore, could face serious philosophical and ethical issues in the community. The hacker or maker movement may have to address ethical issues regarding the use of free open source products. Admittedly, it is impossible for the Arduino company to completely control the use of Arduino products, as software and designs of hardware are shared on the website. However, the company tries to minimise the risks of product use for unlawful or inhumane purposes with the rules in the agreement. The trademark, however, is a tool that protects the logo of the company from manufacturers who do not make a royalty payment to the company; it cannot stop users or manufacturers from using software and designs of Arduino in their customised devices without the Arduino trademark logo. The companies based on open source production principles rely on a trademark to distinguish between official products and clones. Intellectual property right tools, neither license nor trademark, cannot be a solution in preventing the use of Arduino boards for inhumane purposes. Violence or terror attacks in society result from complicated social, political and economic problems, and do not have simple solutions.

The company also struggles against the counterfeits of Arduino, forbidding use of the Arduino symbol on devices produced by other manufacturers. Arduino designs and software are open and shared on the website free of charge and any companies can manufacture clones of Arduino and sell them on the internet much cheaper without obtaining permission. Chinese clones in particular are very popular on online shopping

websites, but some users claim that the clones are of lower quality than the original Arduino (Arduino.cc, 2012). The Arduino company, in a bid to guard against counterfeits, has made the trademark logo much clearer, and the company calls on users to purchase original products to support the open source community.

> The current price of Arduino, even if a few euros more than clones, help us fund and create developing new open source hardware, the documentation, CE/FCC certification, carbon offsetting, quality control, community management, publishing tutorials, make donations to other open source projects, hosting/maintenance website and forum (millions of users!) (Arduino.cc, 2018d).

Purchases of original Arduino products help in the creation of a fund used for the development of new open source hardware projects. Thousands of community hackers make contributions to the process of production of Arduino components, developing software code and designing hardware. However, manufacturers outside of the Arduino community can make profits from Arduino designs and software, and this opens up a process of exploitation in the community. The design and software are outputs of the labour of members of the community. Developers and designers make considerable contributions, and typically spend much time and effort in the creation of designs and software. The manufacturers who do not invest money in the design and software, therefore, can make much more profit from FOSHW products whose intangible goods are freely available on the internet. Without paying a salary to designers and developers, the companies can of course manufacture FOSHW products at a much lower price. To increase the profit margin, manufacturers can also introduce low-quality materials in the production of open source goods. The Arduino company struggles with unofficial manufacturers who sell clones bearing the Arduino trademark. It is impossible to stop the sales of non-original Arduino goods.

Volunteer labour provided by the Arduino community is not just exploited by manufacturers who do not contribute to the community; there is also an exploitative relationship between the Arduino company and the community. The community consists of thousands of developers, designers, hobbyists, and users around the world, but the company is only made up of a small number of professionals and founders running websites, forums, and mailing lists. The owners of the company are also the holders of the Arduino trademark in receipt of a royalty from the manufacturers selling the Arduino boards. Accordingly, the Arduino community is divided into two sections: those who are

professionals of the company making income from the Arduino projects, and those who mostly provide unpaid labour and do not profit from the projects.

Education is one of the most important missions of the Arduino community. The microcontroller is a tool used by educators and students to develop devices in the field of the IoT robotics; design; art at universities; teaching and learning innovative techniques at secondary school; playing with toys to introduce physical learning and buildings skills, and logic and problem solving at primary school (Arduino.cc, 2018d). Arduino boards are utilised by students of all ages from primary school pupils to university undergraduates. The community intends not only to teach the use of technology with Arduino boards but also to explore new teaching methods with the boards. Cuartielles, who is one of the co-founders, asserts that:

> Back in 2012, I was given the challenge of bringing project-based learning to my first group of upper secondary schools in Spain. I realised at the time that almost no one was addressing the needs of educators when introducing curriculum. Therefore, I decided that we had to put educators at the centre of our concept and help them find creative ways to use technology in the classroom. Arduino Education is not just about making interesting projects with students; it is also about getting acquainted with developing technologies and new methods of teaching (Cuartielles, cited in Arduino.cc, 2018e).

Arduino intends to develop an educational style for students lacking a sound technical background. They would become part of the process of technological production and innovation through the use of cheap and simple microcontrollers. Being open source hardware projects, Arduino boards are much cheaper than proprietary boards, and today, Arduino is one of the most popular microcontrollers for hobbyists, makers, and students (Klingeman, 2013).

It is important to note that Arduino microcontrollers allow students to promote their creative activities in the classroom. Students can acquire technical skills and learn how to develop technology. Hobbyists and students can develop their hacking activities thanks to cheap and simple open source microcontrollers. Learners can also join FOSHW communities that are organised on the internet and in Hackerspace. Hobbyists in this way get more skills and experience and can become hackers who actively contribute to FOSHW projects. The most important point is that students who benefit from Arduino boards in the classroom can improve their knowledge in technological development. As I said before, open source hardware projects can be changed and modified. Therefore, enjoy significant autonomy to develop new technology or a new machine with Arduino

microcontrollers. This autonomy increases the creativity of hobbyists, students and hackers and makes the production of technology enjoyable.

Analysis of the Arduino Community

The Arduino community consists of thousands of developers, designers, hackers, makers, hobbyists, and millions of users, and also has a wide range of communication platforms, from forums, mailing lists and social media to hackerspace. In my research, the Arduino developers' mailing list has been chosen for the gathering of primary source material, for corpus and thematic analyses. Arduino as a FOSHW community has a vision of creating a free open culture where knowledge is much more accessible. Education is performed within the free open source system where cheap and simple open hardware microcontrollers can play a vital role in the learning process of students and hobbyists. Hackers, on the one hand, can lead the development of new technological devices and software, and on the other, drive the creation of a new culture based on peer production.

The Arduino developers' mailing list includes hundreds of hackers who make great contributions to the community. In this part of the chapter, I will initially set out a corpus text analysis. The concepts used by developers on the mailing list and during interviews were coded. I focused on the repetition in the transcriptions and in the corpus analysis I identified the themes. I examined power relations among developers on the Arduino mailing list. I also carried out 13 interviews with developers on the mailing list and collected data from the interviews and mailing list archive to submit them to thematic analysis.

The mailing list consists of a large amount of data including developers' conversations between April 2013, when the mailing list was set up, and December 2016, when the data collection process ended. The data has been classified with AntConc, and I have obtained a list of the 50 most common words showing their keyness value on the mailing list (see Appendix 1).

The developers use the mailing list productively, getting together with peers to share knowledge, code, design, or to discuss ideas. The developers' mailing list, as is expected, contains quite technical details and discussions regarding the development of software and designs of Arduino projects. Concepts such as "library", "hardware", "code", "folders", and "files" are core elements of the production process of open source hardware. The hackers share the files, including code and design, with each other on the mailing list. Collaborations among developers are the most important activity of

production. The terms “request” and “support”, therefore, are frequently used on the mailing list in calls for collaboration. Technical talk is the dominant discourse; political or ideological discussions hardly ever take place on the developers' mailing list. Additionally, the community has an agreement, which includes the terms of service decided by the Arduino company; developers joining the community must obey the terms of the agreement. In the previous chapter, we looked at the RepRap developers' mailing list that contained serious political and ideological debates over the community roadmap, because the RepRap community did not have a formal agreement on the terms of service normally decided by a company.

However, the interviews shed some light on the social and political aspects of Arduino. Before analysing the interview data, I need to give some detail on the demographic background of the interviewees. Most of the interviewees are male (12 out of 13 interviewees), over middle age and highly skilled hackers and scholars. The demographic information of interviewees is shown in Appendix 2.

It is clear that the numbers of active, young, poorly educated and female developers in the Arduino community are low, as in the RepRap community. According to my observations, the number of female users is very low not just on the developers’ mailing list, but also in the forum. Highly skilled hackers in the Arduino community are not so young, as FOSHW projects are much complicated, and likely require greater experience and skill. Senior or retired developers too, may have much more free time to participate in the community discussions. One of the interviewees claims that:

> Generally, I think retired people have a lot of free time, and so they can be interested in this project. They do not need any salary, just fun. Actually, I expected that young people would generally be interested in this project between twenty and thirty. But the reality is different… I think many people who I would consider my peers, aged wise are people who are senior enough in their careers. They have free time to do [this project] (Interview with ArdM04).

The Arduino community is a multi-national platform comprising developers from different countries. However, the interviewees in my research are from the USA and European countries where the majority of the design takes place. In other words, all interviewees among the most active developers on the mailing list are citizens of developed countries, an important consideration in understanding their motivations and practices. Even so, in terms of consumption, Arduino’s products are currently popular all around the world, with millions of users. Chinese manufacturers selling Arduino boards are particularly well known on the internet, but I did not encounter developers from the

Far East or developing countries during the interview process. The other interesting finding is that the community is male-dominated; just one of the 13 interviewees in the interview series is female. During the data gathering, I encountered only one female developer in the Arduino community.

According to the GitHub survey, 95 % percent of respondents of the survey are men, while just 3% are women. 1% is non-binary (Opensourcesurvey.org, 2017) It is clear that there is a big gender imbalance among the contributors of GitHub. Joseph Reagle (2013) claims that the gender imbalance mostly results from the culture, dynamics and values of free open source communities. He also adds,

> First, free culture can be unappealing to those unable or unwilling to hew to the stereotypical features of the online geek (*i.e.*, an identity associated with an intense and narrow interest and argumentative style). Also, these communities' openness means that a minority of difficult members (including, for example, a sincere misogynist or an insincere troll) can disproportionately affect the tone and dynamics of interactions. Finally, the ideology and rhetoric of freedom and openness can then be used to (a) suppress concerns by labeling them as "censorship" and, to (b) rationalize low female participation as simply a matter of women's choice (Reagle, 2013).

The values of FOSS and FOSHW communities and some features of hacker culture can have a relationship with the male-dominated ideology. As stated previously, communities generally have a benevolent dictatorship, and the leaders and co-developers are mostly men. Women, therefore, can experience some obstacles in their participation in communities, or may simply not feel comfortable within a male dominated community and be unable to express themselves properly; certain aggressive men may not let them develop a new argument. It is important to note that the gender gap is an important problem in both FOSS and FOSHW communities. Furthermore, the communities mostly consist of well-educated developers from western countries. There can be various reasons for the gap. Arguably, male-dominated communities constitute one of the most significant challenges of the FOSHW in the formation of democratic and fair platforms. The diversity issue in both communities requires further discussion but I do not have primary interview data to look in depth into the reasons why diversity in FOSHW communities is problematic.

Hackers of the free open source movement sometimes conflict with each other in FOSHW communities. I argue that particular hackerrs conduct these conflicts in the Arduino community. This is demonstrated by hacker respondents from the Arduino community who provide important evidence during the interviews. Certain themes,

including “the issue of open source”, “the issue of Arduino clones”, “sharing in the Arduino community” and “the issue of intellectual property right tools”, “fun in the Arduino community”, “the structure of the organisation” and “collaborations in the Arduino community” have been selected for thematic analysis. The themes chosen for this chapter are slightly different from that of Chapter 5, which analyses the community that produces open source self-replicating machines, whereas the Arduino community develops open source microcontrollers. Also, the structure of the Arduino community differs from that of RepRap, as the themes on the Arduino mailing list and in the transcriptions are slightly different from that of the RepRap mailing list and interviews.

1-The Issue of Open Source

Open source: As previously explained in the RepRap chapter, the concept of open source has been debated by hackers again and again since hardware hacking consists of both intangible and tangible goods, not just intangible goods as with software. It is obvious that the distribution of tangible goods is impossible on the internet. Nonetheless, the manufacture of Arduino boards requires raw materials and energy. Therefore, it seems that open source as a term can be restricted to accessing intangible goods such as designs, software, and knowledge in the Arduino community.

> ... Open source hardware is looking at design files as open source. One of the questions is that their sources are accessible or not. So, if you do have sources so when you design a piece of hardware, you can make a combination of software like the firmware pieces. And then there is the assembly step, and finally, you have your product, so each of those steps is many more layers required to have open hardware (Interview with ArdM30).

In the production process of hardware designs, there is no difference between FOSS and FOSHW. Both movements are motivated to access code and design files to learn how to produce intangible goods such as code and designs.

> I would describe open source hardware as hardware released under an open source license, so people have access to the design files (both schematic and PCB layout). I use it a lot, and this was also how I learned hardware design in the beginning, as you learn a lot just by looking at what other people have done. It also allows you to easily make your own design based on another product (Interview with ArdM33).

> By open source, I mean you can use the code as long as your projects are open source. I usually download an open source library to understand what they've done and then rewrite it for my purposes. If I wanted to do something, I would look for a chip that has several library options like maybe two or three people's written libraries because often, the best way to understand it and

> debug it is to look at what different people have done and have gone okay well (interview with ArdM51).

For some hackers, the concept of open source refers to the learning process. The meaning of open source does not just involve accessing code or design for software; it also references code and algorithms to learn how code and design developed. As stated previously, one of the main motivations of hackers in the Arduino community is education. Arduino microcontrollers, on the one hand, might provide students and amateurs with a significant advantage in the building of customised electronic devices suited to their needs. The community, on the other hand, tries to encourage students and hobbyists to become part of coding and design production, keeping code and design open for those who are willing to learn how to produce sources. In this way, the creativity of hackers is promoted. This cannot be called a technical choice; it is also a process of cultural production where collaboration is a crucial element in the production and distribution of products. The concept of open source can refer to a simple and cheap product on the Arduino mailing list.

> Open source hardware brings what used to be a costly, expert process to more people/makers/tinkerers for much cheaper. Making your own hardware device used to cost tens to hundreds of thousands of dollars of investment and development. Now you can buy an Arduino or Raspberry Pi for $10 and invent things very quickly and easily through a simplified software development chain and quick electronic prototyping. OSHW allows you to design hardware at a higher level without the specialised knowledge and time required for proprietary solutions (Interview with ArdM34).

Arduino is a platform where users become producers of the devices they require. The Arduino community is also part of the DIY movement as Arduino boards are just tools used for developing more complicated devices that meet specific needs. In terms of accessing the means of production and being part of the production of Arduino, simplicity and cheapness of Arduino microcontrollers can be important for hobbyists in trying to develop their electronic devices at home. Being cheap and accessible, Arduino boards allows hackers to build customised devices:

> My dream is that in 10 years, any normal sane person off the street could assemble their own product from open-source parts and software to meet their exact need. It reminds me of the aliens in “The Mote in God's Eye” (by Larry Niven and Jerry Pournelle), where they could invent and build, on the spot, whichever devices or tools they needed at that moment (Interview with ArdM34).[53]

[53] The Mote in God's Eye is a science fiction novel written by Larry Niven and Jerry Pournelle (see Bookshop.org, 2021).

Low cost, simple microcontrollers are important tools for hackers and hobbyists in the building of open source devices that meet their needs. People have a chance to become prosumers of technology, with free open source microcontrollers that allow users to change or modify software and designs (see Roberts and Cremin, 2019). Another question discussed among Arduino developers is whether or not open source products should be sold.

> There is a different discussion of selling or not selling. I am very practical when it comes to this and personally as I said what matters to me is okay. You want to pay for your work. It is fine. Here is the money, if I like what you do, I come to buy it. But, on the other hand, I want it to be open anyway; I like the code to be able for me to look into it and eventually make modifications if I need to. So again, to me, there is a different discussion about paid software or paid hardware licenses. Versus not paying from the discussion of openness and not openness (Interview with ArdM37).

As I mentioned in Chapters 4 and 5, the relationship between the free open source movement and commercialisation has been a significant topic for two decades. The OSS movement attempts to reduce the ideological tensions between commons and market; it also facilitates hackers' plans to make money (Berry, 2008). However, it seems that the tension is still there in the Arduino community. Hackers trying to make a living from open source products can run into difficulties in free open source communities:

> At the end of the day, developers need to pay their rent. They need to eat, and they need to build sustainable business models around what they do, and it is important to understand them as well. When we go to a music concert, we are very happy to pay for the tickets, and if it is a musician that we like we have to pay a higher ticket. But nobody is willing to pay a higher ticket for a piece of software because they do not really like the programmers (Interview with ArdM37).

Drawing an analogy between a singer and a developer, I think, is not helpful in the promotion of open source hardware commercialisation, nor is it helpful to those who try to make a living from open source products. A song or piece of music is mainly produced by a person or a group of people, not based on community production. A freelance developer, not part of an open source community, can develop software and hardware products without the help of the open source movement, and then sell them to their own customers with or without source code. Accordingly, users must make a payment for software or hardware designs developed by the freelance developer. However, developers do not easily sell free open source products because the open source or CBPP is essentially community-based production, and open source products are the property of the community. In other words, property in open source communities refers to the right

to distribute, not to exclude (Weber, 2004). Furthermore, open source projects cannot be just anyone's private property in the community, since productive fun labour of hackers creates value in the market. If this value is appropriated by a company or a developer, volunteers become hyper-exploited of (Kostakis and Bauwens, 2014; Harvey, 2017). Volunteers are not paid, but their creativity and free time in this context serves commercial interests. Volunteers in this sample are exploited to "a greater extent than the proletariat" (Ritzer, 2014, p.18).

Any number of developers can make contributions to a specific open source product, and the source code of software and designs are freely distributed on the internet at practically no cost. Any user can more or less access free open source products on the internet at no charge. In the same way, many users download musical albums and live recordings on the internet without making payments to singers and musicians. Even though songs and music are the result of commons-based production, singers can make money from live performance of their music (Shotwell, 2020). Developers building reputation in open source communities can also sell their services to customers using free open source products. Many hackers belonging to the free open source movement make a living this way (see Raymond, 2001).

The concept of open source also refers to faster innovation in the digital field, where the distribution of software and designs is quite rapid and easy.

> It is easier to innovate on a project when others can build on top of it. Again, this could lead to faster innovation and better products (Interview with ArdM03).
>
> … I think that [open source] can also be a good thing in the long run as it spurs innovation (Interview with ArdM07).
>
> Open source empowers the people who are willing to invest time to learn. They get not locked in by companies. This freedom to modify enables faster improvements of products to sometimes even innovative level (Interview with ArdM10).
>
> …speed of development is good. let's say that you make something that's very relevant and people get interested then the speed of development will be super-fast (Interview with ArdM37).

The participation of many developers in the production of open source projects works to create a vast labour force that in turn spurs innovation in the digital field within a short timeframe. Open source technology, by keeping source open, paves the way for a grassroots movement based on CBPP, whereby many developers from around the world participate in the production and distribution process of digital goods thanks to network

platforms. Production of free open source projects, for this reason, becomes quicker than that of proprietary companies in which a group of designers and developers lead the production of digital goods. The production process in FOSHW communities is much more dynamic and effective than that of proprietary companies because users of open source products usually become producers of FOSHW goods (see Raymond, 2001). An open source community can reach thousands of contributors who invest their time and voluntary labour in a project.

Arduino is one of the most popular of the FOSHW projects, developed by many contributors around the world. Nowadays, the Arduino community creates a great range of innovative microcontrollers and boards that have a prominent position in the market. It is important to note that the voluntary labour of thousands of contributors and open source policies plays a central role in the speedy innovation of Arduino boards. In particular, I think, the creativity of contributors is a significant factor in quicker innovation. As I have argued, creativity can be possible with co-creativity (Buzgalin and Kolganov, 2013). The collective production process receives significant support from hackers and volunteers. The interactions between the supporters of FOSHW promote intellectual production. The playfulness of hacking gets significant attention around the world. The more hackers have fun, the higher their contributions to open source communities (Hausberg and Spaeth, 2018), and innovation speeds up in this way.

Even though some open source projects do not have the potential to make a profit, these open source products are still available, and developers can insist on the development of the projects solely for their use value. In this way, the FOSHW movement prompts innovations in the digital field without having to take into account whether goods have an exchange value or not. One of the interviewees claims that “in the case where the original manufacturer goes out of business or otherwise stops working on a product, there is a bigger chance that a (version of a) product will stay available” (Interview with ArdM03). This is quite an important point for a technology production policy favouring ordinary users seeking higher quality, safety and utility in contrast to technology companies commercial priorities.

FOSHW advocates argue that they can provide users with safer and more reliable services than those of proprietary companies. One of the interviewees asserts that "one benefit would be that if more hardware would be open-source, buyers can see more clearly what they're buying, and better evaluate reliability, security and privacy (either by doing this themselves or by trusting others to do so)" (Interview with ArdM03). They claim that

open-designed hardware enables users to exercise “control” of the devices they use to customise the hardware products in accordance with their needs. Additionally, they note, users have the capacity to remove particular parts of the designs which seem incorrect or unsuited to their needs. In this way they argue that users can take control of technology rather than let technology control them.

2-The Issue of Arduino Clones

Clone: The Arduino community, as with many open source hardware communities, keeps all sources, design, and software, open to all those seeking to use them in their customised devices. As it is an open source policy, any user can download and distribute software and designs of Arduino boards on the internet at low cost, although the Arduino company does try to extract royalty payments with their trademark from companies that manufacture their boards. Arduino then uses the income for the development of Arduino projects and open source-based business. Nonetheless, some manufacturers reject payment of a royalty to the Arduino company even if the design and code of the Arduino community are used in the manufacturing process. These products, which are not manufactured by the Arduino company or official manufacturers of Arduino, are called “clones”. Manufacturing and selling of Arduino clones with the Arduino name and trademark but without the payment of royalties is deemed “counterfeit”, an unacceptable situation for the Arduino company. The Arduino company allows developers to clone microcontrollers for home use without the Arduino name and trademark. The real problem is with unofficial manufacturers. Using the Arduino trademark without the permission of the company raises legal issues regarding IPR.

> From a hardware point of view, I think that the Italian Arduino manufacturers (companies) regret that the boards were made open source hardware. The software is another issue. The open source hardware (board design, drawings, etc.) has been a great opportunity for Chinese produced clones. These cheap boards [clones] make hardware available to schools, hobbyists, etc. of only a few dollars. The original Italian boards are much more expensive (> 10X). The open source software side is very different. There is not much contribution from Chinese and the other manufacturers for boards. (Interview with ArdM20).

As stated above, Chinese manufacturers usually do not always make a royalty or other payment to designers and software developers for production of Arduino designs and software. Therefore, the clones produced by Chinese manufacturers may be much cheaper than the official Arduino boards. This, on the one hand, can be an advantage for users in

terms of accessing microcontrollers with much less expensive costs. On the other hand, it could be regarded as exploitation by members of the Arduino community. Almost all Arduino sources are produced by the community involving thousands of members who are hackers, designers, developers, advocates, and activists. But manufacturers, who make no contribution to the community, make a profit from Arduino boards. This means that the productive fun labour or creativity of thousands of developers serves the manufacturers pursuit of profit, although producers do not in the main make a living from their contributions to Arduino. The co-founders of the Arduino company are the more privileged members of the community compared to ordinary members who develop software and design new model boards. The co-founders are a small group making money from Arduino projects in the community, and these people have a serious problem with other manufacturers producing clones of Arduino without paying royalties. Besides the company, most developers in the community do not benefit from royalty payments because the trademark belongs to the company.

Furthermore, one of the developers in the community worries that open source hardware, for example Arduino, may boost unemployment if developers and designers are not paid for their labour in the production of intangible goods of open source projects. He asserts that "as for risks, I think open hardware, in some ways, lowers the barriers to the widespread use of automation technology, which is potentially harmful to some job markets" (interview with ArdM07). The idea of the clone takes on a mainly negative connotation, usually linked to the hyper-exploitation of community members by manufacturers who do not contribute to the community. The cloning industry, therefore, can pose a threat to a jobs market where designers and software developers struggle to make a living with their skills and labour.

Even though most contributors cannot make money from official Arduino products, and just a small number of founders and professionals of the Arduino company directly profit from the sale of official products, the contributors can acquire a good reputation through their efforts in the community. This in turn allows contributors to join other digital projects in which developers can be paid for their contributions. The cloning industry, therefore, can directly harm the marketing interests of the Arduino company and indirectly undermine the job market. Manufacturers no longer need designers and software developers since they have easy access to software and designs on the Arduino website. This is a dilemma triggered by the tension between the market and the commons. Moreover, one of the interviewees is concerned about the quality of clones:

> I think the real problem is that there is a growing issue. The Chinese PCB manufacturers can churn out these big open source projects very cheaply. But they often do not have a very long shelf life, and I buy Chinese clone Arduinos all the time for the kits, and they do not work. But the problem is if you are on eBay, you just see £4 for Arduino. I will get that without thinking about the risk. So, the problem is that this kind of thing brings the Arduino name down because you have got all these cheap clones there is no Quality Assurance unless you go to Arduino and buy it from them, but then it's a lot more (Interview with ArdM51).

The primary purpose of the free open source movement in the hardware field is to provide people with designs and software to build their customised devices at home through an open access policy to knowledge and intangible goods. In this way many ordinary people become part of the production process of technology.

Production of technology at the moment is mostly under the control of giant technology cartels that keep all sources of products closed to protect their economic interests. For example, Apple authorised several companies to manufacture and sell cheaper Mac clones to broaden the Mac market between 1995 and 1998. However, the move foundered, and Apple lost a considerable amount of money on the clone program. When Steve Jobs became CEO in 1997, he renegotiated the clone licenses to promote Apple's royalty. He left the clone licenses out on Mac OS 8. The authorised clone era ended in 1998 (Knight, 2014). In this way, Apple reintroduced strong intellectual property rights policies, to squeeze the cloning industry and thereby sustain its own profits. The cloning industry essentially serves the distribution of FOSHW products around the world by reducing the cost of products. Cloning is also feasible in desktop manufacturing, as an alternative to Chinese mass production. If a developer wishes to manufacture an Arduino board at home for their own needs, simply for use value, this does not come as a problem to the Arduino community or company.

One of the main issues with respect to cloning is that unofficial manufacturers do not contribute to the Arduino community. The Arduino company does not completely control the manufacture of Arduino boards even though it is the holder of the Arduino trademark. Cloning Arduino, therefore, is also seen as a risk, potentially causing terrible problems.

> …there are tons of clones and they scare me to keep me up at night. I mean one of them is obvious right in sharing this information. There is always the chance that someone will use it to do something that you find horrific. And you know I every night worry about if somebody one of these days going to use Arduino to make the bomb or to make something terrible like that. (Interview with ArdM04).

So, there is a risk of clones being low quality and destroying reputations. Even though the FOSHW movement encourages users to copy or rebuild open source projects by keeping all source open for quicker, cheaper and more effective innovation, cloning of Arduino with the Arduino name and trademark is unacceptable to the Arduino company due to the decrease in revenue from the trademark. This seems a little paradoxical for the free open source movement as people voluntarily participate in the production process, allowing for the reduction of product costs, more rapid innovation, and production (at least initially) for use value. The Arduino trademark is not directly about speedier innovation, cheaper products or user freedom- it is about the interests of the company.

As discussed previously, the main priority for FOSS is to keep all source open. Users can use free open source goods for any purposes such as distribution, modification and sale. The company puts itself in a privileged position in the market with the trademark, giving it the rights of use of the Arduino name and logo. As stated previously, Arduino is also the name of the community, but no one other than the company has a right to use the community's name on their products. A similar discussion occurred in the RepRap community around the application of non-commercial license.

The bad feeling over cloning demonstrates the tension between the commons and the market. The Arduino company, with its trademark, endeavours to control the market share of Arduino boards created by the commons-based Arduino community. But it would seem impossible to deal with this process because it is not just conflict between company and unofficial manufacturers. There is also a tension between the Arduino company led by a group of co-founders and holders of the Arduino trademark, and the Arduino community which includes a high number of contributors who for the most part do not have a claim on the Arduino trademark. There is a tension in the cloning of Arduino boards. On the one hand, cloning implies the freedom to use, change and modify open source hardware. Clones also make Arduino microcontrollers cheaper in the market, and students and hobbyists can easily gain access to microcontrollers to perform hacking activities such as assembling machines or producing new tech goods. On the other hand, the cloning industry can exploit the creativity of hackers and volunteers and damage the job market in which designers and developers seek paid employment. The industry fosters the hyper-exploitation of hackers. As discussed above, some developers (communitarians) in the Arduino community demand that any Arduino Foundation should transfer money from the Arduino company, the legal holder of the Arduino

trademark, to the Arduino community. However, such an Arduino Foundation has yet to be established, in spite of Banzi's promise in 2016.

3-Fun in the Arduino Community

As stated before, entertainment is an important motivation of hackers (Torvalds, 2001), but having fun refers to hacking activities that produce unstandardised projects. In this sense, there is a strong relationship between having fun and creativity. Hackers may learn new things in the community and can further contribute to the community if they can pick up new skills from other hackers. Hackers see this interactive process as intrinsically enjoyable.

> Hello! I'm a college freshman who's been using Arduino for a couple of years and programming (mostly Java) for much longer than that. I've been looking for good projects to gain experience programming and I thought I would try to contribute to this project! I've had a lot of fun with Arduino and I would love to help out (ArdM21 from the mailing list).

Hacking is fun as hackers have the autonomy to create something new, but hackers mostly use the notion of fun with free time. Some hackers believe that only free time activities can be fun. One of the developers from the mailing list asserts that:

> I've just started electronics and coding 1 year ago. All I do for Electronics/Arduino is of private interest. And I've just started my job career. I can imagine to maybe switch my job to something like this since my current job is something mostly different (more pc and networking). Since it makes so much fun but consumes a lot of time and effort, I maybe want to do this as a job (ArdM15 from the mailing list).

> I read your text [X]. Thanks a lot that gave me some new ideas. Especially with the fact that if my hobby is my job it won't be my hobby anymore (ArdM15 from the mailing list).

As has been previously explained, the line between work time and free time has become more indistinct (Hesmondhalgh, 2010), but it seems that some developers see hacking activities as hobbies occurring in free time, for the purposes of fun. One developer claims that "Generally, I think retired people have a lot of free time, and so they can be interested in this project. They do not need any salary, just fun" (Interview with ArdM04). The problem is that in contemporary capitalism, even the hobbies and free time of hackers are exploited by the corporations (Kostakis and Bauwens, 2014; Harvey, 2017). The products developed in free time have potential market value. Hackers can ultimately make a living from having fun in their hacking activities. There is no longer significant tension between leisure time and work activities. The concept of productive fun labour, therefore,

underlines the hyper-exploitation of the hacker creativity in FOSHW communities. As argued earlier, fun labour is productive because it is a creative activity creating value in the market. Hackers or capitalists can make a profit from the products developed through fun labour. It is fun because hackers have fun when doing hacking activities. It is labour because the creative activities of hackers and volunteers can be exploited by the firms or the leaders of the community.

4-Sharing in the Arduino Community

As noted in Chapter 2, sharing is one of the most significant elements of CBPP. However, the concept of sharing is somewhat unclear in the FOSHW movement. For the FOSS movement, sharing refers to the distribution of code or knowledge. However, hardware projects consist of tangible and intangible goods, and the term "sharing" is not sufficiently clear, whether sharing activities include tangible goods or not. It is important to note that sharing usually has a positive meaning among the developers in the community. Here are a series of statements made by developers on the mailing list and during the interviews.

> It is a great way to share ideas build on other people's ideas and get yourself known (Interview with ArdM06).
>
> The most important part of open source is the knowledge that is shared (Interview with ArdM34).
>
> We share files for people. To share data with them to all are sorts of different things (Interview with ArdM34).
>
> I am happy to share knowledge and techniques (Interview with ArdM72).
>
> I would like to share the hardware and software I designed (ArdM95 from the mailing list).
>
> Thanks for sharing your experience with porting (ArdM45 from the mailing list).

The idea of sharing is used for "ideas", "knowledge", "files", "data", "techniques", "designs", "software" or "code" and "experience". All these elements are intangible outcomes of hardware projects. In this sense, it can be said that sharing activity is limited to just intangible products in the Arduino community. Sharing is also accepted as an individual activity:

> …there was a strong desire that the platform we built be open and accessible to that community in a way that encouraged community collaboration, openness, and sharing … I think we all have a culture of individuals sharing, rather than individuals collaborating (Interview with ArdM07).

Sharing can be seen as one of the main elements of free open source culture directly associated with individuality. Interviewee ArdM07 does not see open source as a community activity rather than an individual activity. Therefore, he uses "individuals sharing" rather than "individuals collaborating". Collaboration is fundamentally the activity of a group of people who help each other. Ergo, collaboration must have sharing activities However, the interviewee separates the idea of sharing from community-based production. This demonstrates an ideological preference of the developer for libertarian rather than communitarian ideology associated with collaboration or solidarity.

Besides, one of the developers on the mailing list indicates the potentially detrimental effect of sharing activity. "…One of them is obviously right in sharing this information there's always the chance that someone will use it to do something that you find horrific…" (Interview with ArdM04). Sharing information on the network platform is a crucial activity in the emergence of free open source culture. In this sense, sharing is an essential part of the free open source production model. Nonetheless, sharing information might entail unacceptable consequences for the FOSHW movement in its production of designs and software for electronic devices. Even though the advantages of sharing information appear to outweigh the disadvantages, it is clear that there is an important ethical problem in the sharing of knowledge or sources of electronic devices that can be used for destructive purposes.

5-The Issue of Intellectual Property Right Tools

License: Copyleft and CC licenses are common in the Arduino community. License should be understood as a legal tool that allows users to share, modify and change code and design of Arduino boards rather than restrict production and distribution of Arduino goods.

> I always release my work under an open source license like GPL v2 and then include a header in the source code. I always try to support open source projects, as I believe we will all benefit more from it compared to each company making their own proprietary code. I release my own work under an open source license work for the same reason and often also under a license where companies have to release the source code for their product under the same license if they develop code based on my work (Interview with ArdM33).

Berry (2008) argues that the GPL essentially stands for the protection of user freedoms. It is one of the most popular licenses allowing users to use and change the licensed

products as they see fit. No one can turn a GPL-protected product into a closed source product restricted by another license. CC is a popular license in the Arduino community.

> I think licenses are important for communities… License is more about saying I made this thing and here is what I give you permission to do with it. I think Creative Commons expresses it best and it is one of the reasons we use CC for our border designs. You know it basically says you can use it under these conditions. And there are many good open source licenses out there. I would not want to say that one is better than another necessarily (Interview with ArdM04).

CC licenses, like GPL, allow users to use and share software and design. Lessig (2004) argues that CC has been created to support "free culture," where cultural goods are produced for people's needs rather than the interests of information cartels. CC is articulated as a protective wall which keeps at bay the intellectual property rights regime and the privatisation of knowledge. There is another open source license used in the Arduino community:

> My favourite license is not really scientific. It is just kind of talking to people. There is like an Apache two license. That has got a bit of patch protection built in. That is typical copyright a bit. It is a permissive license so other people can use your material (Interview with ArdM30).

It is important to note that GPL, CC, and Apache licenses are popular among hackers in the Arduino community.[54] The concept of license mostly alludes to copyleft or open source licenses, and the license, in this sense, has a positive meaning in the Arduino community. Even though license attends to be a tool of copyright used by information cartels to restrict flows of information, copyleft and open licenses are important instruments in hackers' hands to eliminate the risk of open source products being turned into closed source products. Hackers intend to boost collaboration between peers with copyleft license, since peer production cannot work without sharing activities between peers online. The interaction between hackers is based on sharing code, design, ideas, information, knowledge, and experiences, and these activities are supported by open licenses. As stated previously, licenses are used as a bridge between intellectual work and intellectual property. Open licenses are mediating tools that prevent open source from being turned into closed source projects, while the companies apply closed source license to turn intellectual works of creators into the private property of copyright holders. It is

[54] The Apache license is an open license, not copyleft. Under the Apache license, you do not have to release modified parts of the software under the same license (Sass, 2020). The Apache license can be also accepted as a commercial license, which refers to "a term used to describe a license used in commerce- can be either open source or proprietary" (Rosen, 2004, p.52).

important to note that companies can use a dual-license to overcome the rules of copyleft or open licenses (see Stanko, 2020). The licenses cannot completely protect open source hardware projects against proprietary companies.

6-The Structure of the Organisation

The Arduino community has an organisational structure that derives from its reliance on the internet. Analysing the structure of the community helps us understand the status of key people within this community. As previously stated, the internet is the central infrastructure of the Arduino community and is used for a number of communicational and documentary needs. In this sense, we might expect the structure of the Arduino community to be horizontal, not hierarchical, reflecting the tendency of internet organisation to be network-based. As we have seen in Chapter 2, the internet is a tool mass self-communication with a decentralised structure underlying its technical design. Indeed, people can and do play an active role in the Arduino community through this network structure. It is certainly the case that the barriers to people joining the Arduino mailing list and creating an account on the Arduino forum are substantially lessened because it is internet-based. There are, however, key groups and individuals on the mailing list with positions and missions, reflecting a hierarchal control structure. One interviewee identifies a number of groups in the mailing list:

> I would say there are three groups. There is a group of developers, and they are sealed in a different sub-group. They would sometimes interact on the forums, but not a lot. They build an email account, and they exchange messages through this account. The conversation they have on email is a very serious conversation which is regarding the future of the platform. And moderators are people that have been around for a long time. They have a good level of speech. They follow good conduct, so we elevate them to take care of the other users. And there are normal users (Interview with ArdM37).

The main groups he identifies in this community are developers, moderators, and users. As I stated before, the developers are the main players at the centre of the community. Users are also the volunteers of the community, reporting bugs and giving feedback on the projects. We see moderators as another group in FOSHW communities, managing the flows of communication on the mailing list or forums. Arduino developers are mostly organised through the mailing list where they exchange ideas. Arduino users generally use the Arduino website or forum to gain access to information, software, and design. Moderators have a duty to organise these digital platforms to enable productive

interaction between users and developers, but the moderators are not community leaders. The Arduino community also has its leaders.

> I will give you an example, there are no leaders, but we know exactly who they are. Arduino say there are no leaders, but we know exactly who they are (Interview with ArdM04)
> First of all, I think it is very important that there should be one voice of leadership. So, on anything official Arduino I will defer to Massimo [Banzi] and David [Cuartielles] because both of them make their livelihood of Arduino. I think it is important that they present leadership. Secondly, I think that the best way to deal with conflict, in general, is to try and treat the other person with respect and their position (Interview with ArdM04).

As explained previously, the founders of the Arduino community, Banzi, Cuartielles, Mellis and Tom Igoe, became the owners of the Arduino AG Company. In the above quote, an Arduino developer accepts Banzi and Cuartielles as leaders. The founders are both the owners of the company and the leaders of the community, which presents a potential conflict of interest. The community is mostly run under the rules of agreement outlined on the Arduino website. The members of Arduino for the most part do not play an active role in the decision-making process of community rules. The leadership of the Arduino community appears to exemplify the so-called "benevolent dictatorship" I have mentioned previously. This leadership, as mentioned in Chapter 4, is a not untypical governing structure in the FOSS movement. GNU-Linux is also a community run by a benevolent dictatorship. The Arduino community, however, is one of the most effective FOSHW communities, and the giant tech players seek to cooperate with it. A developer explains this cooperation in the following quote:

> We sign deals with Intel, Microsoft or Samsung because they are interested in the real community and they know they cannot build it themselves. They have tried like the makers Intel, but they cannot. Because the value of a community like ours is built on a day to day operation. You do not make it with money. You make it by being there working with people becoming trustworthy. The other thing they can try to do is get a little bit of it by paying us to collaborate on projects, so we have a consultancy model. We worked together on the projects, and we can do it because we have this value. I mean that value is what makes us sustainable (Interview with ArdM37).

Tech giants benefit from the Arduino community by making payments to the Arduino company. We must note that the company, in this way, makes a profit from the value generated by the community. Tech giants cooperate with the Arduino community because the community-based production provides tech giants with an opportunity to accumulate capital through voluntary labour supplied by the Arduino community. In the previous chapter, David Harvey (2017) argues that the accumulation of capital based on unpaid

labour constitutes a form of hyper-exploitation. There is a considerable risk of hyper-exploitation in the Arduino community if Arduino contributors continue to play a passive role in the decision-making process over the future of the Arduino community. Tech giants continue to use the services of the community to make profit rather than Arduino microcontrollers used for the benefit of society. There is a major contradiction between the interests of tech giants and the needs of society.

The Arduino community has a top-down management model. The rules of the community are mainly decided by the company founders. The relationship between the community and the company is unhealthy as the community is effectively a R&D department of the Arduino company. Hackers do not discuss the roadmap of the community nor do they have the right to decide the future of the community. Hackers do not have strong autonomy like the hackers of the RepRap community. I believe hackers in the Arduino community to be less creative than hackers in the RepRap community, as the latter has a horizontal organisation and does not need a consensus in the community for contributions to projects. I do not believe that forking in the Arduino community is as favoured as it is in RepRap community. As said before, the RepRap community encourages hackers to fork their designs; in this way, the RepRap community has a diverse range of designs. The speed of innovation is the priority in the RepRap community while the commercialisation of Arduino boards is the most important issue for Arduino company and Arduino community leaders. The most marked conflict in the Arduino community is over the Arduino trademark; in other words, about intellectual property rights, under which intellectual work becomes intellectual property.

7-Collaboration in the Arduino Community

Developers and users have a wide range of communication platforms on which to contact each other, not just mailing lists or forums. Phone, Skype, Twitter, and Facebook are also favoured communication tools among developers. Some interviewees gave me a list of communication channels used by developers in the Arduino community:

> We use social media platforms like Google Groups, Twitter and increasingly Facebook. In the early days of Air Quality Egg, there was a lot more energy around in-person meetups, hack-a-thons, and the like. We are also (founding) members of our local Makerspace (Ithaca Generator) (Interview with ArdM07).

> Open Source: Arduino forums and developers' mailing list and Github. Github repos of the various Arduino libraries, filing issues, and pull requests.

> Getting help from Atmel, they even lent one of their own developers to write the USB MIDI implementation for us (since it could be used on all their chips as an open source library). Bluetooth developer meets up on meetup.com. The MIDI Association is attending their MIDI over BLE meetings at NAMM.
>
> Not open source: Apple Bluetooth developers' mailing list, Broadcom forums, hiring consultants for EE, ME, ID (Interview with ArdM34).

Most developers do not know each other personally; face-to-face communication is not a common activity in the community. The internet as a mass-self communication tool allows people to interact with peers in different parts of the world. GitHub is a popular digital platform in the Arduino community, as it is in RepRap. The communication tools listed above are mostly internet-based. Thanks to these tools, the Arduino community has acquired an international dimension with thousands of developers and millions of users of different nationalities. Makerspaces or fablabs are new physical places where hackers or makers come together to share their experiences with each other: "The FabLab conferences happen a lot, […] I will make some of the connections there. I have got an international group through FabLab where I talk to them one on one" (Interview with ArdM30). It is clear that physical spaces represent a new communication platform for the hacker movement.

Arduino developers are part of the FOSHW movement, but most developers can use closed source software or communication tools if the closed source alternative is better or more user-friendly. However, one of the developers is strictly against the usage of proprietary software or devices if an open source alternative exists.

> Everything I use is open source. I have three or four computers, and all of them are running Linux, so my whole operating system is free software/ open source depending on the software packages. In my day-to-day work, I force my students to use open source because I tell them I cannot open this file I am sorry. So, they have to give me in a format that is compatible with the open source system. Everything is open source so we are trying to make it effective so that anybody can replicate the whole process we are open sourcing the whole process of designing things. Because we want anybody to be able to follow this process, so it is very important for us (Interview with ArdM37).

Berry argues (2008: 147-181) that the free open source movement is based on a set of ideas which draw on concepts of freedom, digital commons, and openness. This ideology is in broad contradiction with the intellectual property rights regime under which big technology corporations take control of production and distribution of knowledge and technology. Changing or modification of proprietary products is usually impossible due to closed source software and design. Hackers may attempt to create a free open source

ecosystem where access to knowledge is made easier, as an alternative to the intellectual property rights regime. Some hackers may therefore refuse to use proprietary products in daily life in case free open source alternatives exist. This is not from a sort of fanaticism that fails to keep up with progress in technology or social development. However, hackers may sometimes force technology users or students to use free open source products. This is a kind of ideological struggle, not just a technical issue. Hackers struggle in the digital field to widen the free open source domain by creating new open source products and encouraging or forcing people to utilise these products. They do not simply encourage people to use the open source products developed by themselves; they also support all open source products that give users the freedom to change, modify and distribute software and designs.

As an illustration, the free open source movement was based on software production in the early years; the movement was mainly interested in the unfettered production and distribution of code on the internet. Hardware companies do not care whether hardware products are compatible with free open source products. In this way, hardware companies have compelled people to use proprietary software compatible with their hardware products (see Stallman, 2002; 2018). This has been part of the hegemonic struggle between proprietary companies and free open source developers. FOSHW projects give hackers the possibility of creating a counter-power to hardware companies that restrict the scope of action of the free open source movement. The movement produces open hardware products that are much more compatible with FOSS. Likewise, the free open source movement can encourage users to choose its products instead of proprietary ones.

The Arduino developer who suggests that students use the Linux operating system and free open source products compatible with Linux, is not just interested in Arduino boards but supports free open source principles by encouraging users to use other free open source projects. Therefore, the FOSHW movement has a vital role to play in the development of the FOSS movement. FOSHW communities create new devices that are more compatible with FOSS, while some computer companies produce closed source hardware projects that are incompatible. It can be said that Arduino boards, as free open source friendly hardware, allow people to build new customised devices suited to their needs, and those devices are more free-open source software-friendly.

Arduino is one of the most popular FOSHW communities to produce software and designs for microcontrollers and boards. It is also a company founded by a group of

project leaders. The rules of service and conditions of the Arduino community are based on the agreement decided by the company, and users and developers of Arduino generally follow the rules in the agreement. In this sense, ideological and political discussions are not common on the mailing list. Commercial activity is significant for the Arduino company, the holder of the Arduino trademark. However, Arduino as a FOSHW community has failed to bring to an end the tension between the market and the commons. The community, on the one hand, tries to create a system where users and developers share knowledge, designs, software, and experience with each other. The Arduino company and unofficial manufacturers, on the other hand, vie with each other for the largest share of the market in Arduino hardware designs – themselves developed by community contributions including those of hundreds of hackers. The themes of "the issue of open source", "the issue of Arduino clones", "sharing in the Arduino community" demonstrate that hackers on the mailing list can have differing ideological backgrounds, in particular libertarian and communitarian. The tension between the market and the commons is a hard reality not only for Chinese manufacturers and Arduino but also between the Arduino company and Arduino community.

Twenty-first century capitalism has not removed the exploitation of labour; on the contrary, this has intensified as tech giants or manufacturers take significant advantage of voluntary labour provided by free open source communities. This process essentially serves to establish an unequal or unjust social system in the digital field, if FOSHW contributors fail to resist current community-based production where voluntary labour feeds the drive for profit, and contributors are excluded from the decision-making process.

Chapter 7: Conclusion

The main objective of this doctoral research has been to provide a nuanced and detailed understanding of capitalist exploitation in FOSHW communities, which I argue is a relatively new area of interest to the free open source movement. The FOSHW movement has provided an important new field of research, with hardware hackers playing a central role. I show that hardware hackers are not just active producers of digital artefacts but also highly skilled practitioners in the field of digital literacy. Some of them also lead struggles for technology users' rights, attempting to safeguard the freedom of individuals which they claim is threatened by the owners of intellectual property rights. These hackers often make a living from the goods they produce or the services they provide, but to simply make a profit from free open source goods is not their main motivation. Nonetheless, we must note that the FOSHW communities includes hackers and activists from a range of ideological backgrounds, notably libertarians and communitarians (Weber, 2004).

The commercialisation of free open source can on the one hand provide hackers with the possibility of an income from their labour, but it results in a contradiction in the motivations for developing free and open source goods and services. The careful ring-fencing of free and open source methods and goods within a corporation has also enabled corporations to make a profit from the use of free open source products (Benkler, 2006). For example, Apple relies on its open source operating system Darwin which underlies its proprietary interfaces (Dillet, 2017); Amazon relies upon free and open source software across the corporation for its digital presence and logistics networks (MacMannus, 2020); Google has open-sourced its Android operating system for mobile phones (King, 2016), and Microsoft, as we have seen, has purchased GitHub (Mackie, 2018) and sought to use free and open source carefully within its formerly strongly proprietary software culture.

Nonetheless, there is not a strong consensus among hackers of the FOSHW movement on the commercialisation of free open source goods and how to develop the relationship between the FOSHW movement and proprietary corporations. In this thesis I have looked at the conversations within FOSHW communities, which involve hundreds of hackers leading discussions on the future of FOSHW projects and communities. Analysing the "hacker ethic" and culture helped elucidate and explain the relationships between the ideas of FOSS and FOSHW. A key part of this thesis involved giving a

history of the hacker movement, especially given the changing meaning of hacking over the last two decades. In particular, I have explored the opportunities and challenges facing the FOSHW movement through the presentation of two empirical cases, RepRap and Arduino. Through these I have attempted to explore the practices and resultant power relations between members of each of the respective communities. As such, the interviews done for this study represent an original contribution to our understanding of the discussions on capitalist exploitation in FOSHW communities.

Summary of The Thesis

I will now briefly summarise the thesis and the contribution of each chapter. The concept of hyper-exploitation was discussed in the first section of the second chapter. The term hyper-exploitation is important because the form of exploitation has changed under contemporary capitalism. Voluntary labour and online-community-based production can provide capitalists with new opportunities to make a profit without paying wages or salary to the worker. In the second section of Chapter 2, the concept of the commons was explored to help understand the theoretical foundations of this formation. If the participants voluntarily and cooperatively produce the resources of commons, they should also benefit freely from common goods in order to meet their needs. Furthermore, there are particular differences between the older commons, which were localised, used and regulated by certain groups. They also included tangible goods, and the new commons (information or digital commons), which are globally available and organised by cyber-collectives, and generally consist of non-rival goods (Bauwens, 2005).

The structure of the digital commons is based on digital network platforms that allow users to create their own digital pools where digital artefacts are created and distributed. The distribution of digital goods on digital platforms is almost free of cost (Rifkin, 2014). The low-cost distribution of digital products represents a significant breakthrough for those who support digital commons. I discussed Free Open Source Software (FOSS) as a CBPP sample. In particular, I explored the hyper-exploitation of hackers in FOSS communities in which hackers give up their creativity and free time. At the end of the chapter, I introduced the main characteristics of FOSHW, which are different from FOSS.

In Chapter 3, I outlined my research methods and the ethical research approach that informed the thesis. I used a triangulation of three research methods; these were corpus

text analysis, interviews and thematic analysis, applied to the empirical cases of RepRap and Arduino free and open source hardware communities.

In Chapter 4, Following Jordan, I divided the history of hacking into four periods: (1) computerization and network technologies; (2) a crackers' golden age; (3) a re-division and resurgence of free software hacking; and (4) a de-differentiation of hacking. Stage four included hacktivism and hardware hacking, and I argued that free open source hardware (FOSHW) was a continuation of the previous FOSS movement at a new level. To scope the thesis and provide focus, I concentrated on stage three and four. At the start of this chapter, the terms hacking, and hackers were examined. Then I discussed the issue of open source communities and the issue of intellectual property rights. Indeed, working together, hackers became active contributors to the emergence of CBPP and the fight for freedom of internet users against the intellectual property rights regime. The hacker has also been a significant part of the movement in the production and distribution of knowledge, independent of university or private labs.

I argue that the mode of production and distribution of knowledge has been greatly transformed through contributions from the hacker movement. Indeed, it has been argued that peer production and distribution of knowledge mean that such knowledge and practices could be liberated from the owners of technology companies (Rifkin, 2014, p.78). Therefore, hackers can, I argue, be in a position to lead the democratisation of the production and distribution of technology, given that many can easily join digital communities and become part of digital projects. [55] [56] It is certainly the case that hackers have pushed the boundaries of the intellectual property rights regime with their technical and social contributions to the digital field. Hackers thereby claim that they are important social actors struggling for a fairer system in which the technology creators and ordinary users can decide how technology is produced or used.

The copyleft license has been one of the most creative tools in the struggle with the intellectual property rights regime (Stallman, 2002). The General Public License (GPL) was developed to facilitate sharing activities between peers, to free the flows of information. GPL itself is a clever activity that hacks the intellectual property rights regime in favour of internet and technology users. Copyleft licenses and CC licenses can

[55] The democratisation of the production refers to participatory production where ordinary people can get involved in the production process.

[56] Digital communities are communities of practice or innovation communities in this context.

play a key role in the protection of the digital commons (Stallman, 2002; Lessig, 2004; Moritz et al, 2018).[57]

The Issue of Hyper-Exploitation

FOSS has played a key role in the market since the 2000s when open source communities worked in collaboration with tech giants. Open source and free software communities have obtained funding from tech companies to develop free open source projects, in return for the use of open source projects with proprietary computer hardware. In this way the system has created a new model for the accumulation of capital, and these tech giants have made major profits (see Benkler, 2006). The most significant source of this profit has been the voluntary, unwaged labour of many free open source contributors.

Voluntary, or what I call "productive fun labour" can play a key role in the production of FOSS projects. Peer production allows individuals to join the production process. Technology users can become producers of technology they use in daily life, not just consumers. As explained in Chapter 4, the FOSS movement conflicted with tech giants who were behind the intellectual property rights regime. The leaders of Microsoft saw the FOSS movement as "a criminal group" that threatened the interests of their company in the early years of the hacker movement. The supporters of the FOSS movement were called a "modern sort of communists" (Gates, quoted in Dean, 2005). GNU/Linux was viewed as a "cancer" in the software industry (Mackie, 2018). However, in later years, Microsoft developed a good relationship with the FOSS movement. In 2018, Microsoft announced the purchase of GitHub, an important platform where hackers shared their free open source products. The other pivotal event in the history of the FOSS movement was Microsoft's decision to use the GNU/Linux kernel on Windows. In May 2019, Microsoft announced that Windows 10 was applying for a Microsoft-built GNU/Linux kernel to improve the performance of the Windows Subsystem. The officials stated that the kernel would be completely open-sourced (Foley, 2019).

An interesting question is why the Microsoft company changed its mind regarding the FOSS movement. It must be understood that the FOSS movement has built a strong reputation by developing high-quality software alternatives. Proprietary companies have faced severe problems in competing with FOSS communities. CBPP has shown itself to

[57]CC and Copyleft licenses can have differences. For example, GPL allows users to use licensed products for commercial purposes, but the Non-commercial CC license does not allow people to commercialise licensed products.

be an effective production model in the software industry, particularly in terms of leading infrastructural software innovation. Another explanation might lie in the use of unpaid labour by capitalists to maximise profit within a new regime of "hyper-exploitation" (Kostakis and Bauwens, 2014; Harvey, 2017).

Some developers who produce FOSS are funded by tech giants, but many contributors to open source projects are unpaid. Wages, paid to workers for their labour power, are by and large not a feature of CBPP. If voluntary labour of contributors serves the movement for internet or user freedom by producing alternative software and digital platforms, voluntary labour can play a significant role in the creation of production system based on open source as an alternative to the intellectual property rights regime. The FOSS movement has shown that another digital development is possible without recourse to proprietary companies. Nonetheless, certain developers, in particular the mostly libertarian leaders of the FOSS movement have tried to develop a working relationship with proprietary companies in order to make money. These developers, I argue, are not in principle against the intellectual property rights regime, they just request some wiggle room within the regime. In other words, these developers seek autonomous spaces in the regime rather than the creation of counter-power, which is an alternative system based on CBPP.[58] Turning voluntary labour into capital can be a significant advantage for proprietary company owners in terms of boosting profits since the companies do not have to pay regular salaries to employees working as software developers or designers. Non-payment to free open source contributors might represent a new phase in the history of capitalism. This is hyper-exploitation because contributors "are exploited to a greater extent than the proletariat" (Ritzer, 2014, p.18). The contributors lack employment security, social security, pension benefits and so on. This "hyper-exploitation" also takes place in FOSHW communities.

The Opportunities and Challenges of FOSHW

Hacking hardware is a relatively new phenomenon in the history of hacking and this thesis is an original case study of the practices and justifications for it. It is also an important topic in hacker groups, heading up a new discussion on desktop manufacturing at home. Hackers become significant actors in the creation of FOSHW projects for the tech cartels who dominate the hardware industry. Hackers have already acquired a strong reputation

[58] Counterpower refers to alternative values and interests defended by social movements and civil society (Castells, 2013, p.52).

in the software industry with FOSS. They are now active in the hardware industry producing hardware design that is suitable for hacking culture.

Hacking hardware allows individuals to play an active role in the manufacture of tangible artefacts at home. As mentioned in previous chapters, the manufacture of hardware projects by the masses has also been termed personalisation of manufacturing, desktop manufacturing or Do It Yourself (DIY) (see Insley, 2011; Kostakis et al., 2013; Wolf and McQuality, 2011). The DIY movement does not just engage in the production of technology; a close relationship has also developed between the DIY and hacker movements around the manufacture of hardware. DIY communities are usually online-based communities in which individuals create new things and share them with others on the digital commons-based network platforms. The communities are quite popular platforms for makers and hackers with high technical and artistic skills. They are free to exchange ideas (through comments and forum posts) and to work together in different ways. DIY culture is rarely motivated by business interests. There is a range of practices characterising DIY communities, including learning, low barrier to entry, creativity, and open sharing. Members of DIY communities also organise in-person meetings for the purpose of creating material objects and social interaction (Kuznetsov and Paulos, 2010).

Hardware hacking, on the one hand, allows the free open source movement to take part in the production of hardware product designs, which are otherwise mostly controlled by hardware companies. The movement, on the other hand, faces a challenge in how to manufacture hardware along the lines of CBPP. While the FOSS movement has managed the production of software, the FOSHW movement has engaged in both design production and hardware manufacture. The production of intangible goods on the internet via the peer-to-peer model is less complicated than that of tangible products since the production and distribution of software are at low cost on the network platforms, and do not require too much capital investment or raw materials. The production and distribution of hardware designs follow the same process as that of software. However, the manufacture of tangible goods by the peer-to-peer system is more complicated as manufacture and distribution of hardware require significant investment and materials. This indicates a tension between the principles of the commons and those of the market over the production and manufacture of FOSHW products.

The change in the production process “from mass production to production by masses” (Rifkin, 2014) through FOSHW can bring about social change. People do not have to be consumers of technological goods produced by proprietary companies

forbidding the modification of hardware designs. Instead, they can produce devices for their own needs and purposes. Individuals can customise technological goods in line with their requirements thanks to open source policies. Having access to the source of software and hardware design enables users or developers to modify technology, given that they can learn how software or design is developed by looking at existing source code.

Access to code or design is bound up with the question of users' freedom and control of technology. People can manage technology by changing the design of free open source products to meet their needs, but proprietary companies do not share the source of software and hardware products with users. Those who use proprietary products cannot change anything on the goods for their own purposes; they must respect the terms of use of closed source products. Closed source technology, therefore, prevents users from playing an active role in the production of technology. Users are seen as simple consumers by proprietary companies, who push a strategy based on mass production. The FOSHW movement can offer users an alternative, custom-made production model in the hardware industry. Customization can be seen as a significant production method for researchers and hackers, as they mostly require specific devices or goods to maintain innovation or to manufacture hardware goods at home. For example, 3D printers, portable machines used for the manufacture of customized hardware, have become quite popular devices among researchers and makers, to obtain craft prototypes (Mavri, 2015).

Free open source 3D printers are important production tools for the hacker or maker movement in the creation of a community where people collectively manage the production of hardware goods. Jeremy Rifkin claims that accessible production tools enable ordinary people to manufacture tangible goods at home without the need of huge machines. As a consequence, capitalism may go into crisis, since capitalists, usually the dominant class, would lose control of the production process (Rifkin, 2014). In a capitalist system, production mainly serves the accumulation of capital. Capitalists fundamentally manufacture commodities not for their use value, but for exchange value to raise their profit margins. The FOSHW movement, however, cares more for the quality of technology, the freedom of users and speedy innovation. It is clear that FOSHW goods require raw materials and energy in the manufacture of hardware, so FOSHW products can also acquire an exchange value. However, the main motivation of makers in open hardware communities is to produce hardware design and turn the design into prototypes for use value. Therefore, the FOSHW movement is not currently as appropriate a vehicle for the accumulation of capital as are proprietary companies.

The Issues of RepRap and Arduino

The replicating rapid prototyper (RepRap) is a free open source self-replication machine that produces most parts of itself (Goldberg, 2018). The RepRap project has become one of the most innovative FOSHW products drawing the attention of numerous hackers who seek to adapt hacker culture to hardware goods (Moilanen and Vaden, 2013). Even though RepRap is mostly associated with 3D printers, these are not simple 3D printers that manufacture tangible goods at home. Replicating itself is the most striking feature of RepRap. The inventor of the project, Adrian Bowyer, decided that the development of self-replicating machines should be governed by the principles of the free open source production model. At the start of the project, a small number of core developers contributed to the RepRap machine, but the project grew to a community of hundreds of contributors in a short space of time.

Bowyer (2011) claims that RepRap machines create "wealth without money" with the self-replicating characteristic. RepRap users, in this way, produce self-replicating machines for their friends without having to purchase another 3D printer from tech corporations. The users simply require raw materials and energy to complete the manufacture of hardware goods. The software and design of the machine are accessible on the RepRap website and GitHub platform. Hackers have made outstanding contributions to the RepRap community regarding how the software of the self-replicating machine should be developed, and the machine assembled. The community has produced and distributed knowledge in the creation of self-replicating machines. Bowyer (2011) also believes that free open source self-replication machines could spontaneously lead a revolution that would allow the working class (the proletariat) to access the means of production. The revolution, in this way, would avoid class war, social conflicts or civil wars in its transformation of society. He calls this revolution, a peaceful transformation, "Darwinian Marxism".

It is a Darwinian process because the revolution is fundamentally based on the proliferation of self-replicating machines. The higher the number of RepRap machines, the greater will be the wealth produced by the machines. Self-replicating machines become significant players in the evolution of society from a system where the production process is controlled by a layer of capitalists to a system in which many people can participate in the production process of tangible goods. The economic power of the capitalists would be undermined by RepRap machines if ordinary people could easily

own and transport the means of production to enable the manufacture of hardware at home. The main difference between Bowyer's and Marxist theory is that the former claims that the evolution of technology is the dynamo of social change while the latter theory asserts that class struggle is the main driver of social transformation.[59] Both theories, however, argue that the change of ownership of the means of production can pave the way for social transformations in which class positions are changed around.

The RepRap community has formed the RepRap Union enabling owners of RepRap machines to share the components of self-replicating machines with the members of the community. This loan system helps RepRappers increase the number of machines through the building of a solidarity network where people share self-replicating machines that create "wealth without money". The RepRap Union has been a pivotal experience for the FOSHW movement since it is mostly interested in the distribution of intangible goods and hardware goods. The RepRap community has extended the scope of open hardware through the sharing of self-replicating machines with others, who can then copy a new self-replicating machine at home. The only thing the person has to do is make a small financial deposit to protect the rights of RepRap machine owners. The loan system provides a self-replicating machine for those who deposit a sum, and the RepRap machine is returned to the owner after copying a new machine. At the end of the process, people are refunded their deposit, and just pay a small amount of money to the owner of the machine. In this way people can acquire a RepRap machine, with the additional expense of raw materials and energy, at the lowest price. Sharing the parts or the whole machine can be useful for people to own and control the means of production at home to meet their needs without purchasing a 3D printer from a company.

I have discussed certain themes in Chapter 5: the issue of open source, the issue of self-replicating, the issue of customisation, fun in the RepRap community, the issue of intellectual property right tools, the structure of the organisation and collaboration in the RepRap community. The term "open source" is ambiguous in FOSHW communities because hardware hacking consists of tangible and intangible goods. Open source refers to keeping software code open in FOSS communities, but it is not clear what the term it means for tangible goods. Hackers in the RepRap community mostly use the term open source for intangible goods such as design, software and information. The RepRap Union has been formed to share self-replicating machines with peers in the community, but the

[59] Marxism is a theory which argues that full public ownership and control of the means of production would end the accumulation of capital and class society (Marx and Engels, 1848; Marx, 1990).

union has not been an effective model. There is no consensus among hackers on the community's chief purpose. Yet, there is an important discussion on the mailing list about whether the RepRap project is non-profit. Communitarian and libertarian hackers have clashed on the use of ads on the RepRap website. Communitarian hackers have objected to the ads of proprietary companies on the website, and opposed FOSHW projects that involve proprietary companies.

The issue of self-replication is one of the most significant topics on the RepRap mailing list. As mentioned above, self-replicating machines are designed to produce "wealth without money". Communitarian hackers see self-replicating machines as an important opportunity to create wealth based on the use value rather than the exchange value. In this way, it is possible to use the creativity of hackers for the benefit of society rather than making money. Self-replicating machines offer users significant autonomy in the manufacturing of portable production tools. Prosumers need not buy 3D printers from proprietary and open source companies. With the necessary raw materials and energy, RepRap machines can copy their components and hackers share these components with other peers in the community. However, libertarians do not see self-replicating machines profitable. As these hackers are not so interested in the dictum "wealth without money", self-replication does represent an effective marketing strategy. They see the RepRap project as a technological development model providing hackers with a great commercial opportunity.

Customisation is another significant issue in the community. RepRap machines might enable hackers to customise the manufacturing of hardware goods. Hackers can have the freedom to change and modify the design and software of RepRap, which are open source. Closed source 3D printers do not allow users to change or modify design or software. Libertarian hackers, therefore, may see customisation as a significant marketing strategy to make a profit from open source 3D printers. Customisability can also play a key role in the production globally of a range of different RepRap designs. With more customisation, hackers are invited to be more creative to adjust self-replicating machines or 3D printers to their needs.

Having fun is one of the most popular motivations of hackers in the RepRap community. Hacking activities are fun because hackers solve problems in an interesting way. There is a strong relationship between hacking as productive labour and having fun from doing something interesting and challenging. As I said before, the line between work time and leisure time is now blurred. Hacking activities are productive labour that takes

place in leisure time. Products developed by hacking practice may gain value in the market. Open source products mostly acquire value in this way. It does not matter whether a commodity is produced in work time or in leisure time if it takes on value in the market. The only difference is that volunteers in open source communities are not paid in return to their contributions while workers working for a firm or factory are paid. Therefore, I call hackers' productive labour "productive fun labour". As stated before, fun labour is productive because it is a creative activity and creates value in the market. It is fun because hacking activities are entertainment. It is labour because the creative activities of volunteers can be exploited by the firms or the leaders of open source communities. The exploitation of productive fun labour is called "hyper-exploitation". The idea of fun is significant in the RepRap community because the idea of fun can obscure the regime of hyper-exploitation of hackers. However, some hackers (especially libertarian) are disposed to make a profit from FOSHW projects. The contributions of thousands of hackers can be converted to capital in the same way as in the FOSHW movement. RepRap machines might replicate most parts of themselves, but open source companies are currently selling RepRap machines.

The RepRap community employs the instruments of intellectual property rights tools. Copyleft and open licenses are popular licenses that allow hackers to use, change and modify software and design. The main aim of copyleft and open licenses do not allow the companies to turn open source projects into closed source products. The RepRap community mostly uses the General Public License (GPL) and Creative Commons (CC) licenses. Some hackers in the RepRap community apply the non-commercial (NC) CC for their RepRap designs. NC licenses do not allow the companies and other hackers to commercialise their RepRap design. Libertarian hackers are strongly against the NC licenses since, as I said before, as they wish to commercialise FOSHW projects. Types of licenses are important in the commercialisation of open hardware. Licenses constitute a bridge between intellectual work and intellectual property. Libertarians seek to make a profit from intellectual works licensed by copyleft and open licenses that allow hackers to sell open hardware goods, but NC licenses do not allow hackers to commercialise intellectual works. They can use products licensed by NC license for their needs but cannot use it for commercial purposes as some hackers, in particular communitarians, forbid those who do not contribute to intellectual work to make it their intellectual property. Here we see a tension between libertarians and communitarians in the RepRap community over NC licenses.

I argue that the RepRap community does not have a strict hierarchy. Even though Adrian Bowyer is the leader of the community, no one is forced to do anything. Hackers can choose a task they wish to work on in the community. The members of the community have autonomy to develop their designs. The forking of RepRap projects is not seen as a threat, and hackers are encouraged to design their self-replicating or 3D printers. There is not a "good" or "bad" idea in the community. Every idea is worth developing. Hackers do not need to build a consensus in the community on any idea or project. With self-replication machines, hackers can copy new self-replicating machines for local people. The RepRap community has a horizontal organisation, in which the creativity of hackers is not limited by a top-down structure.

Arduino is the other empirical case chosen for this research and its analysis of the FOSHW movement. As a community, Arduino engages in the production of software and design of microcontrollers. Arduino boards include a mechanism that reads inputs and turns them into outputs. These boards can be the microcontrollers of many of the machines used by ordinary people in everyday life, or indeed researchers seeking more complex devices. Arduino is also the name of the company that holds the Arduino trademark. As explained in Chapter 6, the Arduino mailing list contains three groups: moderators, developers and users. However, I argue that the Arduino community, including online and offline platforms, consists of three main groups: contributors, who are the largest group to voluntarily participate in the production of Arduino; the owners of the company- a small number of people running the company; and official or unofficial manufacturers, who make and sell Arduino goods. The owners of the Arduino company are also the co-founders of the community. The company seeks to make profits from the Arduino operates off its trademark, giving the owners a royalty payment from manufacturers producing and selling Arduino boards. Unofficial manufacturers, however, do not make a royalty payment to the company. There is a serious tension between the company and unofficial manufacturers. Furthermore, most contributors do not make a living from Arduino boards while the company and manufacturers profit from the community-based production. There are tensions not just between the Arduino company and unofficial manufacturers, but also between the contributors and the company, and the contributors and manufacturers.

FOSHW is community-based production in which hackers, makers, and designers for the most part engage voluntarily in the production of software and design. In the main, the motivations of contributors to improve and develop technical skills and

gain a reputation in the community, as opposed to making money. The Arduino company, however, pursues a profit-oriented business strategy with its trademark, and extraction of royalty payments from official manufacturers that sell Arduino microcontrollers. The owners and employees of the company represent a small number of people who make a living from Arduino boards developed or designed by the many contributing creators of the community. The productive fun labour of the contributors feeds the accumulation of capital for the company and manufacturers. Contributors are the most disadvantaged group in the community while unofficial manufacturers are the group that benefits most through production and sale of counterfeits of boards bearing the Arduino name and logo. Unofficial manufacturers, in this way, do not have to hire developers or designers in the production of design and software of microcontrollers. They can easily access all source of the boards on the Arduino website and other sharing platforms such as GitHub.

The FOSHW movement can have a detrimental effect on the job market if unofficial manufacturers keep using free open source design or software for hardware goods without contributing to the community. Furthermore, the Arduino company does not share income from the trademark with contributors. The relationship between company and contributors, in this respect, is rooted in a regime of hyper-exploitation where contributors do not even receive wages. In the traditional capitalist system, companies have to pay salaries or wages to workers in return for their labour power, but manufacturers or open source companies do not have to pay wages to the contributors. This is one of the weakest aspects of the FOSHW movement because the contributors do not have employment security or a regular income to survive.

I have discussed certain themes in Chapter 6, which are mostly similar with Chapter 5 the issue of open source, fun in the Arduino community, intellectual property right tools, the structure of the organisation, and collaborations in the Arduino community. Hackers in the Arduino community have similar discussions with that of the RepRap community about these themes. Chapter 6, however, has different themes to discuss, including: Arduino clones, and sharing in the Arduino community. The cloning industry is one of the most important issues in the Arduino community. Manufacturers produce and sell the Arduino clones. The Arduino company allows users to produce or manufacture Arduino microcontrollers for their needs, but the company does not allow anyone to use the Arduino trademark on a clone and commercialise it. The company calls a clone using the trademark without permission “counterfeit”. As stated above, the cloning industry gives rise to hyper-exploitation in the Arduino community. The Arduino

company and manufacturers can make a profit from the sale of Arduino microcontrollers produced by the productive fun labour of thousands of developers and designers.

Additionally, the term sharing covers intangible goods. Hackers mainly share design, software and information. It is impossible to manufacture Arduino boards at home without the tools of production. Hackers do not discuss how they share these tools with each other on the mailing list while RepRap self-replicating machines allow users to copy the components of the machine and share them with other members of the community.

The thematic analysis carried out on the sample of hackers from the RepRap and Arduino communities illustrates that there is an ideological struggle between libertarian and communitarian hackers in the FOSHW communities. Communitarians are a group of hackers trying to create an alternative platform in which users and developers can benefit from the digital commons, and where production and consumption of software and hardware goods are collectively managed by contributors or supporters of the FOSHW movement. Communitarians give priority to the use value of goods enabling users to bring technology under control. However, libertarians are mostly interested in the business opportunities presented by the FOSHW movement. Libertarian hackers, in fact, do not intend to create an alternative system based on CBPP to the intellectual property rights regime. They are not happy with the strong intellectual property rights policies, but if the regime were to loosen their strict policies and allow hackers to manage peer production in the digital field, libertarians would be disposed to develop a closer relationship with proprietary companies for money making purposes. These hackers can see the FOSHW production model as a new business strategy in the market. The exchange value of free open source products is as important as their use value to the libertarians.

Another problem for the FOSHW movement is that some open source projects can become closed source projects for commercial purposes. For example, the MakerBot company was formed by the members of the RepRap community to lead the manufacture of free open source self-replicating machines, but the company decided not to share the source of products with users a few years after the company was founded. The countless contributions of hackers have been appropriated by the MakerBot company, as MakerBot design was based on RepRap design. One of the company co-founders, Zachary Smith, was fired because he insisted on following free open source principles. The RepRap community, however, encourages people to develop a business strategy for the proliferation of free open source self-replicating machines. More than one company sells the components of RepRap machines. The community mostly uses copyleft licenses and

other open licenses rather than applying a common trademark of the RepRap logo or name. The Arduino company, on the other hand, owns the Arduino trademark. The co-founders of the company had a disagreement regarding the control of the trademark. In short, there was an internecine struggle between the owners of the Arduino company as to who would become the holder of the trademark. The Arduino community also applies copyleft, open licenses or CC licenses for the legal protection of free open source goods, to block the conversion of open source into closed source products. The trademark is an instrument of intellectual property rights used for business purposes, not for the protection of free open source principles.

Thematic analysis reveals a contradiction in the RepRap community. FOSHW communities on the one hand can lead social change by liberating the means of production from proprietary company owners. The communities can be effective platforms where people become part of designing and manufacturing open hardware projects. On the other hand, capitalism comes to manipulate the principles of CBPP in the digital field, just as the commons is limited to the sharing of intangible goods on network platforms.

The hackers' communitarian ideology supports the principles of the commons in the community. They are predominantly concerned with sharing, collective production, collaboration, and cooperation. Libertarian hackers see the marketing of FOSHW projects as an important opportunity to make money and to make the projects players in the global arena. Marketing, on the one hand, offers hackers opportunities to make a living, but on the other damages the principles of the free open source movement, highlighting the contradiction between the commons and the market.

The companies can abandon the free open source production model to make much more profit by restricting access to the source code of digital goods. Tech companies based on free open source principles can immediately stop sharing source of digital goods and they can adopt closed source policies for technology they produce, as MakerBot did. The temptation to turn open source companies into proprietary companies becomes one of the most significant challenges facing the FOSHW movement. It should for this reason develop strong ties to social movements that demand a fairer, freer and more egalitarian world, to keep free open source principles away from tech companies. Money making is not the main motivation of hackers, whereas tech companies are focused on the potential to market FOSHW.

The structures of the RepRap and Arduino communities differ. The RepRap community has a benevolent dictatorship that leads hackers in the production and

distribution of RepRap projects, but hackers can have a strong autonomy in the community in terms of the development of technical skills and ideas. Bowyer provides hackers with a platform where there are no strict rules on how the community is run. Hackers can disagree on technical or social issues in the community, but the leader of the community does not interfere in the disputes between hackers. According to Bowyer's philosophy based on "Darwinian Marxism", the best idea is going to win at the end of the day, so each hacker should follow their own path. The RepRap community has developed a wide range of RepRap machines around the world through this approach. There are also some companies that produce and sell RepRap machines. The RepRap leadership does not view the fork of the project as a serious threat that could damage the principles of the community. Hackers, therefore, can found a company to sell their RepRap designs. There are no copyright or intellectual property rights tools to restrict the fork of RepRap or the sales of RepRap machines. Hackers in the community might benefit from copyleft or open licenses to facilitate the distribution of software and design of self-replicating machines.

The structure of the Arduino community breaks down into three main groups: The founders of the community (also the founders of the Arduino company), contributors and manufacturers. The community has a website, Arduino.cc, where hackers have access to software and design of Arduino boards. The website contains the terms of agreement decided by the Arduino company. The Arduino developers' mailing list is managed by Massimo Banzi and his friends. The community has a strong benevolent dictatorship that decides how the community is working. There are no discussions and debates on the Arduino mailing list about the roadmap or main rules of the community since they are decided on by the founders of Arduino company. Hackers in the Arduino community do not have strong autonomy. Therefore, the Arduino community does not have rich data on creativity, fun and ideological discussion as much as that of the RepRap community. The top-down structure of the Arduino community reduces the autonomy of hackers while the horizontal organisation of RepRap allows hackers to fork their projects. We should note that horizontal organisations have a positive effect in boosting hackers' creativity and productivity.

As explained before, the Arduino company receives a royalty payment from the official manufacturers using the trademark on the Arduino microcontrollers. Contributors do not get involved in the decision-making process even though they manufacture Arduino boards without the trademark. The microcontrollers cannot be manufactured at

home as easily as self-replicating machines, so hackers can require some complex means of production to manufacture Arduino boards locally. The manufacture of Arduino boards at home, therefore, is much more difficult than that of RepRap. Individuals do not have the kind of strong autonomy in the Arduino community as that enjoyed by developers in the RepRap community. The disagreements among the founders of the Arduino company regarding the holding of the trademark caused a split in the community in the early years of the 2010s, although the community reunited again in the second part of that decade. The disagreement mainly stemmed from the control of revenue the Arduino company. The conflict between the founders of the company did not derive from the principles of peer production; it arose from the Arduino company market strategy and the struggle between the founders who took control of the trademark. The disagreement on the market strategy caused chaos and splits in the community. In other words, the arguments over market strategy undermined the values of commons and peer production in the Arduino community.

I argue that hackers can further radicalise their contribution as active players in the creation of open source goods through the FOSHW movement. This includes taking care to prevent technology corporations or capitalists from manipulating free open source policies. Hackers might also lead the further democratisation in the manufacture of hardware at home or local economy. The FOSHW movement has already made a remarkable contribution to this through the production of self-replication machines or free open source 3D printers which are, crucially, portable, and an affordable means of production in the manufacture of hardware.

Manufacturing hardware products with self-replicating machines enables hackers to create a support network among users in the extension of the commons. RepRap Union has been a key social network sharing tangible goods, and the idea of an offline commons has been promoted. But for more effective CBPP, the requirement is to develop a commons-based society where the idea of commons is not just realised in the digital field, but also in manufacturing, farming, the city, education and so on. In this way, the online commons is backed up by the offline commons, and it can then be difficult for dominant tech businesses to manipulate the principles of CBPP for their own ends. To manufacture complex FOSHW projects, the movement needs to develop and maintain cooperative structures of organisation where hackers collectively manage the manufacture of safe, quality and affordable digital goods. Correspondingly, Trebor Scholz (2014) suggests “worker-owned cooperatives”, based on collectively owned and democratically

controlled businesses. These cooperatives can deliver hardware hackers social and economic rights such as pension funds, health insurance and regular salary. However, the most important thing is that cooperatives "allow workers [designers or developers] to exchange their labour without the manipulation of the middleman" (ibid). In this way, productive fun labour of hackers does not have to feed into capital controlled by technology corporations. As stated previously, designs of hardware are global, manufacturing of hardware is local. I argue that cooperatives, therefore, should include local users, not just hackers. Local users might play an active role in the organisation and governance of cooperatives. Technology production can in this way become social production, benefiting society rather than the interests of technology giants. The cooperatives can be social spaces where technology producers and users become an important part of social production, and where the hyper-exploitation of hackers' productive fun labour does not exist. Hackerspace, makerspace or fablabs can be significant partners to the cooperatives, but all contributors, I believe, should be able to participate in the decision-making process in movement organisations such as foundations, cooperatives, hackerspaces, and online communities. Productive fun labour can also be used for projects that offer users a safe and affordable service. But the future relationship with technology giants or capitalists will remain a fraught issue for maintaining independence and adhering to the principles which underpin these free and open source communities, as I have shown above. Surely, hardware hackers can play a key role in the extension of the commons offline, through their technical, social and political experience and skills. If firms continue to appropriate productive fun labour, commercial exploitation will ensue; as creativity and fun are never in short supply. Cooperative-based hardware manufacturing can be an important topic in future research.

The participation gap among developers along gender lines, education or experience, and nationality, also represents another challenge to the FOSHW movement. Even though the hacker work ethic is against gender discrimination, it is clear that there is a huge gap between men and women in the RepRap and Arduino communities. I did not find any clear data or expressions that insult women or humiliate women hacking skills, but it is obvious that the number of female developers in both communities is very low. There are a number of reasons why female hackers are not as active as male hackers, including the culture, dynamics and values of free open source communities (Reagle, 2013). Hacking hardware can be understood as a culture created by highly educated, middle aged men from western countries. It is important to note that the demographic

backgrounds of developers are limited to the most active developers on the RepRap and Arduino mailing list, but this group provides a majority of mailing traffic and circulation. For the true democratisation of hardware production, a large and varied layer of society, including people of different gender, sexual orientation, education level and economic background, need to become involved in the production process and the decision-making process. This is critical for the avoidance of bias against certain groups in society, in the field of hardware design and manufacture. The diversity issue in the FOSHW movement requires closer scrutiny in future research.

By analysing the mailing list archives of RepRap and Arduino communities and drawing on interviews with contributors to these online communities, I argue that hacker/makerspaces remain important sites for hackers to share experience in the building of hardware products. Future research could address hacker/makerspaces and practices in related areas.

The hardware cloning industry is one of the most important challenges facing the Arduino company and community. But there is insufficient data on manufacturers' selling of FOSHW products without making royalty payments to companies, individuals or communities. How do unofficial manufacturers benefit from FOSHW? Why do they not make a royalty payment to the trademark holders when they are not even part of the production process? Future academic research might yield a deeper understanding of the cloning industry and motivations of manufacturers.

Voluntary labour and an ageing contributor group play key roles in the production and distribution of FOSHW products. In the free open source system, voluntary labour can be converted to capital, subsequently appropriated by the leaders of communities under the intellectual property rights regime. Future research might focus on a political economic analysis of open source companies, but also consider how the organisation of these critically important and innovative spaces of creativity are maintained and sustained. This sustainability, I argue, should incorporate the understanding of the movement that I have outlined in this thesis, and also seek to provide both adequate funding models, and means to enrol new and younger programmers, designers and users into the communities.

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Appendix 1: Corpus Text Analysis

Table 9.1: Corpus Analysis of the Archive of RepRap Mailing List

#Keyword Types: 3087
#Keyword Tokens: 68136
#Search Hits: 0

Rank	Freq		Keyness	Effect	Keyword
1	1177	+	12858.36	0.0178	firmware
2	851	+	9358.27	0.0129	extruder
3	918	+	5816.41	0.0136	print
4	710	+	4982.28	0.0107	printer
5	811	+	4238.64	0.0118	code
6	586	+	3803.59	0.0088	fix
7	811	+	3493.49	0.0116	machine
8	766	+	3130.89	0.0109	software
9	320	+	2847.51	0.0049	pla
10	428	+	2467.09	0.0064	hardware
11	690	+	2312.79	0.0096	design
12	324	+	2125.47	0.0049	patent
13	556	+	2001.98	0.0079	source
14	160	+	1750.54	0.0024	commercial
15	1248	+	1745.14	0.0122	make
16	245	+	1527.12	0.0037	controller
17	395	+	1462.78	0.0058	file
18	552	+	1208.17	0.0073	idea
19	109	+	1207.18	0.0017	quality
20	624	+	1080.83	0.0078	open
21	154	+	1075.93	0.0023	customise
22	96	+	1052.07	0.0015	gpl
23	115	+	961.28	0.0018	forums
24	170	+	886.09	0.0026	feedback
25	233	+	882.93	0.0035	cheap
26	75	+	830.61	0.0011	ubuntu
27	72	+	797.39	0.0011	stratasys
28	362	+	787.6	0.005	material
29	376	+	765.91	0.0052	project
30	153	+	757.26	0.0023	cost
31	70	+	756.97	0.0011	cutter
32	71	+	744.21	0.0011	upload
33	68	+	742.64	0.001	slic
34	67	+	742.01	0.001	forum
35	65	+	719.86	0.001	license
36	190	+	718.11	0.0028	community
37	224	+	712.26	0.0033	free
38	76	+	708.28	0.0012	warping
39	63	+	697.71	0.001	sell
40	62	+	686.63	0.0009	wiki

41	66	+	684.86	0.001	heatsink
42	491	+	656.03	0.0061	support
43	97	+	652.51	0.0015	self-replication
44	244	+	645.04	0.0035	user
45	134	+	637.64	0.002	developers
46	59	+	613.44	0.0009	ads
47	59	+	608.82	0.0009	assemble
48	90	+	606.95	0.0014	backlash
49	63	+	603.4	0.001	slicer
50	67	+	602.85	0.001	fun

Table 9.2: Corpus Analysis of the Archive of Arduino Mailing List.

#Keyword Types: 2721
#Keyword Tokens: 85696
#Search Hits: 0

Rank	**Freq**		**Keyness**	**Effect**	**Keyword**
1	1496	+	15952.24	0.0229	ide
2	2069	+	14283.84	0.0303	code
3	1989	+	12319.06	0.0287	library
4	572	+	5769.34	0.0088	api
5	773	+	5271.42	0.0117	hardware
6	923	+	4874.29	0.0136	file
7	592	+	4738.97	0.0091	sketch
8	756	+	4470.49	0.0114	core
9	361	+	3916.8	0.0056	spi
10	423	+	3729.05	0.0065	folder
11	312	+	3405	0.0048	upload
12	362	+	3164.33	0.0056	compiler
13	282	+	3131.29	0.0044	bootloader
14	366	+	2969.26	0.0056	interrupt
15	389	+	2949.76	0.006	buffer
16	653	+	2904.78	0.0096	user
17	259	+	2862.75	0.004	atmel
18	316	+	2755.45	0.0049	compile
19	257	+	2502.45	0.004	interrupts
20	282	+	2491.08	0.0044	gcc
21	611	+	2401.98	0.0089	function
22	483	+	2311.29	0.0072	pull
23	243	+	2249.56	0.0038	uno
24	201	+	2151.33	0.0031	teensy
25	179	+	1987.45	0.0028	printf
26	171	+	1898.62	0.0026	toolchain
27	364	+	1897.19	0.0055	platform

28	376	+	1790.44	0.0057	print
29	202	+	1673.49	0.0031	cores
30	215	+	1657.71	0.0033	programmer
31	287	+	1621.47	0.0044	directory
32	477	+	1597.24	0.0069	source
33	218	+	1498.72	0.0034	sketches
34	133	+	1476.66	0.0021	avrdude
35	202	+	1429.82	0.0031	compatibility
36	216	+	1413.87	0.0033	header
37	254	+	1307.64	0.0039	forum
38	321	+	1265.41	0.0048	request
39	113	+	1254.59	0.0018	hardwareserial
40	666	+	1224.68	0.0084	support
41	168	+	1195.67	0.0026	bug
42	120	+	1192.31	0.0019	download
43	115	+	1188.3	0.0018	cosa
44	268	+	1177.8	0.0041	implementation
45	138	+	1175.19	0.0021	blob
46	176	+	1169.9	0.0027	variant
47	191	+	1167.38	0.0029	install
48	153	+	1155.35	0.0024	functionality
49	216	+	1151.43	0.0033	fix
50	145	+	1143.08	0.0022	reset

Appendix 2 -Demographic Backgrounds of Interviewees

Table 9.3: The Backgrounds of RepRap Interviewees

Name	Age	Gender	Education	Country
ReRM02	43	Male	Master	Serbia
ReRM03	52	Male	Bachelor	Germany
ReRM04	39	Male	Bachelor	Portugal
ReRM05	65	Male	PhD	UK
ReRM06	55	Male	Collage	New Zealand
ReRM09	70	Male	Bachelor	USA
ReRM10	45	Male	High School	USA
ReRM26	42	Male	Bachelor	USA
ReRM33	61	Male	Bachelor	UK
ReRM41	64	Male	Bachelor	Sweden
ReRM61	41	Male	PhD	UK

Table 9.4: The Backgrounds of Arduino Interviewees

Name	Age	Gender	Education	Country
ArdM03	32	Male	Bachelor	Netherlands
ArdM04	50	Male	Bachelor	USA
ArdM06	48	Male	PhD	USA
ArdM07	36	Male	Bachelor	USA
ArdM10	56	Male	Bachelor	Netherlands
ArdM20	41	Male	High School	Sweden
ArdM30	45	Male	Bachelor	USA

ArdM33	24	Male	Bachelor	Denmark
ArdM34	39	Male	Master	USA
ArdM37	44	Male	PhD	Spain
ArdM51	38	Male	Bachelor	UK
ArdM61	55	Male	Bachelor	Germany
ArdM72	26	Female	Bachelor	UK

Appendix 3- Interview Questions

Interview Date:
Interviewee:
Transcription Date:
Transcript Author:

Introduction: I am undertaking a three-year doctoral research project, which is broadly investigating Open Source Hardware projects and communities. I am conducting a series of interviews with users and developers of OSHW projects as a means of informing this study. These interviews will be an important part of data-gathering for my research. I will ask each interviewee the same pre-defined questions, but take the liberty to, as the conversation goes on, ask to follow up questions that I formulate on the spot. It will take about thirty-fourth minutes. I am recording the interview.

1) Tell me a bit about yourself and your background please (Age, job, gender, country) and how did you get involved in IT and Open Source technology?
2) How do you use open source hardware in daily practice?
3) Why do you use or support OSHW projects instead of buying a proprietary one? What are your main motivations?
4) How do you contact the other users or developers to solve the problem related to products or making contributions to production process?
5) Are the types of legal protection, including licence, patent, etc, important for you when you decide to buy or contribute an open source hardware products? If yes, why does it matter for you?
6) Does any of your income come from open-source hardware and what do you think about relations between OSHW communities and corporations or non-profit organization?
7) What kinds of the real benefits and potential risks do FOSHW projects bring for society and what kinds of changes are you expecting in the future especially in economic, social and political fields?