Digital Fabrication and Open Concepts

An emergent paradigm of consumer electronics production

Pär Andersson

Department of Informatics
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For Holly

Death is not final… only a misunderstanding of time

Abstract

Open Source och relaterade mjukvarukoncept och utvecklingsmodeller är vid det här laget allmänt bekanta och har varit föremål för många studier. Open Source Hardware är mindre spritt och studerat, och så även emergent teknologi som för in traditionellt industriella tekniker som 3D-printing, laserskärare, och CAD-baserade produktionsverktyg i mindre skala i hem- och hobbymiljöer. Dessa ämnen har främst studerats ur mer renodlat tekniska perspektiv, snarare än att sättas i samband i en vidare kontext. Denna kombinerar internet som infrastruktur och socialt medium för kunskaps- och resursdelning; open source-koncept; de möjligheter som tillgängligheten av mer och mer kapabel och överkomlig hårdvara byggd på öppen design bereder; och andra relaterade socio-tekniska fenomen vilka börjat framträda de senaste 5-10 åren.

I denna uppsats undersöker jag denna större kontext. Uppsatsen har utförts i form av en litteraturstudie av existerande forskning inom ovanstående diskreta områden, och i den mån de finns även dess inbördes relationer. Denna kontext framträder som ett emergent paradigm kring produktion av hemelektronik, och även som exemplifierande trenden av teknologins fortsatta intåg som allestädes närvarande i våra liv och vår omgivning. Resultaten indikerar en gryende förändring i hur vi interagerar med teknik, vilka som gör det och varför, i vilka kontexter, och ett framträdande av en ny ekonomi. Jag visar på att ytterligare forskning behövs, och att perspektivet bör flyttas från att analyseras enbart i diskreta termer som teknik, open source-principer, DIY et cetera, utan även till vad som framstår som resultatet där dessa konvergerar, den naturliga konsekvensen av ett folkligt anammande av denna teknik och open source-koncept.

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1. Introduction

DIY electronics is not a new idea; already in the 1920s DIY communities would form around amateur radio hobbyists, relying on amateur handbooks and social meetings to facilitate and pursue their hobby. From the World War II ban on amateur radio, through the pirate radio stations of the 1960s and punk aesthetic zines of the 1970s, a rebellious attitude pervaded. In the 1980s, low-cost MIDI equipment enabled people with no formal training to record electronic music (Kuznetsov & Paulos, 2010), something that continues to this day. During the same time, hacker culture emerged from communities of computer hobbyists creating, exploring and exploiting software systems (Kuznetsov & Paulos, 2010). With the rise of open-source software and commons-based peer production models, and the introduction of the Arduino microcontroller; Raspberry Pi single-board computer; RepRap 3D printer; and equivalent open-source/hardware/design based products over the last five to ten years, a foundation has been laid for layman production of consumer electronics. Where open design, open source, and open source hardware are concepts each defined by manifestoes of criteria, open concepts as used within this thesis is a more fluid term and describes the *realpolitik* of their combined implementation within maker culture. Open concepts-based digital fabrication may not necessarily strictly adhere to openness by formal definitions, but is built upon a foundation and environment created and inspired by open ideals and practices.

1.1 Statement of purpose

The purpose of this thesis is to examine the landscape of DIY digital fabrication of electronics artifacts based upon open source, -hardware, and -design concepts. While there exists varying degrees of previous research on discrete topics pertaining to this matter, little has been done to unify them under a wider context. Communities, ideological-philosophical undercurrents, maker demographics and motivations, hardware and software platforms, tools, and applications will be examined. By doing so I hope to create a better understanding and a more clear view of what is emerging around digital fabrication based on open concepts, and to inspire and create a jump-off point for future research.

1.2 Research questions

In my thesis I address these research questions:

- What is the landscape of open concepts-based digital fabrication?
  - Which are its defining features?
  - How does it manifest?

By "landscape" is meant the sum of aspects of *how*, *with what*, *by whom*, and *why*. Ideological underpinnings, demographics and motivations, tools and technologies, current and indicated future developments, prerequisites, and other such characteristics of an emergent social-technological phenomenon.

2. Background

In this chapter I will describe six core concepts of open concepts-based digital production: Commons-based peer production, open design, open source and free software, open source hardware, and Third Wave and DIY Maker culture. In addition, I also describe 3D printing, a common method for digital fabrication.

2.1 Commons-based peer production

As defined by Benkler & Nissenbaum (2006):

> *"COMMONS-BASED peer production is a socio-economic system of production that is emerging in the digitally networked environment. Facilitated by the technical infrastructure of the Internet, the hallmark of this socio-technical system is collaboration among large groups of individuals, sometimes in the order of tens or even hundreds of thousands, who cooperate effectively to provide information, knowledge or cultural goods without relying on either market pricing or managerial hierarchies to coordinate their common enterprise."* (p. 394)

Benkler & Nissenbaum (2006) proceed to give the "tens of thousands of succesful free software projects" as the best-known examples of commons-based peer production, mentioning the GNU/Linux operating system, the Apache webserver, the Perl programming language, and the BIND domain name server as the most famous examples. The field of open concepts-based digital fabrication as defined in this thesis, is typically either a direct example of commons-based peer production, or derivative of previous commons-based peer produced work through the use of hardware and software developed under such a model.

2.2 Open Design

Open design is a method of design and manufacture of physical artifacts, based on open source principles and the increasing access to tools of fabrication. The Open Design Manifesto by Ronen Kadushin (2010) defines the method as consisting of two preconditions:

1. An Open Design is CAD information published online under a Creative Commons license to be downloaded, produced, copied and modified.

2. An Open Design product is produced directly from file by CNC machines and without special tooling.

and further states:

> *"These preconditions infer that all technically conforming open designs and their derivatives are continuously available for production, in any number, with no tooling investment, anywhere and by anyone.*
>
> *[...]*

The designer should always be acknowledged as the original creator and owner of the design, even in case of a derivative design. If an open design is produced for commercial use, the designer has to agree for such use and get paid." (pg. 1)

While Kadushins preconditions of open design apply well to the phenomenon of open soncepts-based digital fabrication (although somewhat overly specific in how it refers to tools) examined in this thesis, the second paragraph is much too strict and too excluding to make open design by this definition applicable as describing this phenomenon as a whole.

2.3 Open Source and Free Software

Open-source software (OSS) is a development model based around the idea that users should have access to the source code and documentation of software and be allowed to modify and redistribute it as they see fit. The primary argument for the open source model is that it inherently leads to higher quality software. Eric S. Raymond (2005) of the Open Source Initiative (OSI) explains:

> *"The core idea of open-source development is very simple: open-source programmers have learned that secrecy is the enemy of quality. The most effective way to achieve reliability in software is to publish its source code for active peer review by other programmers and by non-programmer domain experts in the software's application area."*

Free (or Libre) software is a particular open source philosophy that puts great emphasis on defining and protecting the *rights* of the user to have this freedom to do so. Richard M. Stallman (2010) of the Free Software Foundation describes free software as a social and political movement.

All free software is open source, but not all open-source software is free software. There is great debate between proponents of either model, aggravated by the two terms often being used interchangeably by individuals less vested in either side. Stallman (2002) argues that open source "misses the point", while Raymond (2007) maintains that the term "free software" is ambiguous and detrimental to efforts of promoting adoption of the open source model in the commercial world. In an attempt to resolve this, the terms FOSS (Free Open Source Software) for software that is free *and* open, and FLOSS (Free/Libre/Open Source Software) as a catch-all term for all types of open source software have been proposed, but neither has been fully accepted and have in turn generated further debate (Stallman, 2013; Raymond, 2009).

The core concepts of open source as defined by the Open Source Initiative ("The Open Source Definition", n.d.) are, in somewhat abbreviated form:

- Free redistribution: Any party should have the right to sell or give away the software as part of a larger software distribution, and without royalties or fees.

- Free access to the source code: The program must include the source code and allow distribution in source code as well as compiled form. The source code should either be bundled with the software or be easily aquired through other means.

- Derived works: The license must allow modifications and derived works, and must allow them to be distributed under the same terms as the original software.

- Integrity of the author's source code: The license may restrict source code from being distributed in modified form, *only* if the license allows the distribution of "patch files" with the source code for modifying the program at build time.

- No discrimination against persons or groups: The license must not discriminate against any person or group.

- No discrimination against fields of endeavor: The program must allow for use for any purpose[1].

- Distribution of license: The rights attached to the program must apply to all to whom the program is redistributed without the need for execution of an additional license by those parties.

- License must not be specific to a product: The rights attached to the program must not depend on the program's being part of a particular software distribution. In other words, it must be allowed to extract and use parts pof the software with the same rights that are granted to the software distribution as a whole.

- License must not restrict other software: The license must not put restrictions on other software distributed alongside said program. For example, the license must not insist that all other programs distributed on the same medium must be open-source software.

- License must be technology-neutral: No provision of the license may be predicated on any individual technology or style of interface.

The core concepts of free software, the "essential freedoms" as defined by the Free Software Foundation (Stallman, 2002) are:

- The freedom to run the program, for any purpose (freedom 0).

- The freedom to study how the program works, and change it to make it do what you wish (freedom 1). Access to the source code is a precondition for this.

[1]Exemplified in no uncertain terms by OpenBSD founder Theo de Raadt (2001) in a message to the OpenBSD source-changes mailing list: "But software which OpenBSD uses and redistributes must be free to all (be they people or companies), for any purpose they wish to use it, including modification, use, peeing on, or even integration into baby mulching machines or atomic bombs to be dropped on Australia."

- The freedom to redistribute copies so you can help your neighbor (freedom 2).

- The freedom to distribute copies of your modified versions to others (freedom 3). By doing this you can give the whole community a chance to benefit from your changes. Access to the source code is a precondition for this.

Functionally they are very similar to those found in the open source definition, but the wording illustrates the difference in goals.

For the purpose of this thesis I will use the term open-source software (from here on referred to as OSS) as defined by the OSI, unless otherwise stated, as the core principles of OSS are the most widely applicable in this context. Some products and projects discussed herein may also be free/libre as defined by the FSF, but a distinction will not be made unless it is relevant to the topic at hand. Should that be the case it will be explicitly noted. I have chosen to avoid FOSS/FLOSS due to their limited adoption.

2.5 Open Source Hardware

Unlike open source, which by now is a well-known concept, open source hardware is less widely publicised. The Open Source Hardware Association (OSHWA) states the principles of open source hardware as ("Definition", n.d.):

> *"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."*

The open source hardware definition mimicks the open source definition, with omissions of non-applicable conditions and the addition of a number of conditions more relevant to hardware. These are (abbreviated):

- Documentation: The hardware must be released with documentation and design files and must allow modification and distribution of the design files. Documentation must either be distributed with the hardware or made easily accessible through other means. Design files must be in the preferred format of of making changes, i.e. the native file format of a CAD program.

- Scope: The documentation for the hardware must clearly specify what portion of the design, if not all, is being released under the license.

- Necessary software: If the licensed design requires software, embedded or otherwise, to operate properly and fulfill its essential functions, then the necessary software must either be released under an OSI-approved open source license, or documentation of interfaces to readily facilitate the writing of the necessary software.

- Attribution: The license may require derived documents, and copyright notices associated with devices, to provide attribution to the licensors when distributing design files, manufactured products, and/or derivatives thereof. This information must be made readily available.

In addition to the OSHWA definition, the Open Source Hardware and Design Alliance (OHANDA)[2] provide a differing definition based on the FSF definition of free software. This definition is nearly identical to the free software definition described earlier, with "device" substituted for "program".

2.6 Third Wave DIY and Maker culture

Stephen Fox (2014) defines three waves of DIY: subsistence DIY (First Wave), industrial DIY (Second Wave), and the new DIY (Third Wave). Within this definition, subsistence DIY is concerned with the production of food and necessities; industrial DIY concerns made-to-forecast kits, such as self-assembly furniture. New, or Third Wave, DIY encompasses what I have called open production in this thesis. Third Wave DIY, Fox (2014) states, "draws upon the read/write functionality of the Internet, and digitally driven design/manufacture, to enable ordinary people to invent, design, make, and/or sell goods that they think of themselves". While the role of openness by formal definitions, such as those provided by the Open Source Initiative or the Free Software Foundation, in Third Wave DIY can be extrapolated from some of the examples given by Fox (2014), it is never explicitly identified as a fundamental, driving characteristic. Maker culture is largely driven by the internet, but there also exists physical gatherings such as Maker Faire, where makers of different groups can intermingle and exchange ideas (Dougherty, 2012).

Maker culture can be seen as the sociological component or manifestation of Third Wave DIY. Dougherty (2012) posits that maker culture, or the maker movement, describes a culture of tinkering, innovation, enthusiasm and collaboration. While the maker movement and maker culture are sometimes used interchangeably, I have chosen to use culture rather than movement (with the exception of in direct quotes) in this thesis as I consider it more neutral. A movement implies a unified political goal to move towards, a strife to effect change. My interpretation is that the maker movement exists within maker culture, but does not necessarily include all who consider themselves makers.[3]

2.7 3D Printing

3D printing, otherwise known as additive manufacturing (AM), is a fabrication process where a 3-dimensional artifact is created by computer-controlled layer-by-layer deposition of material. There exists a large number of AM technologies, serving various purposes and with various capabilities, advantages and limitations (Conner et al., 2014). In this thesis, 3D

[2]http://www.ohanda.org/
[3]Compare to the dichotomy of free/libre software versus open source as described in chapter 2.3

printing and AM will be used in the general sense, focusing on 3D printing as a concept rather than examining discrete implementations on the technical level.

Originally highly expensive industrial devices, 3D printers have in recent years become increasingly affordable and feasible for private acquisition and use. While the same is true for CNC machines, laser cutters, and other tools of production that are also part of open concepts based digital fabrication, I have chosen to focus on 3D printers in this thesis, as they are the most novel technology and serve well as as an ideal example of home fabrication tools. For all general intents and purposes of their practical implementation in open concepts-based digital production, the conclusions drawn regarding the role of 3D printing applies to any tool in the same category.

2.8 Background summary

As will be seen as we proceed, there are too many caveats to describing open concepts-based digital fabrication solely and strictly in terms of commons-based peer production, open design, open source, or open source hardware; there are too many deviations while still retaining enough similarity that a unifying term is useful for research and discussion. Open design, free/libre/open source, and open source hardware all carry political-philosophical implications, while I am looking to identify the social-practical context in which these concepts are used for the design and manufacture of consumer electronics.

3. Methodology

I strongly believe that the dichotomy between objectivist-epistemological and subjectivist-ontological approaches[4] is illusory, and rather that they are complementary tools, each suited better for certain tasks or contexts. I believe that generally speaking, the most reliable results (depending on context) are produced when these approaches are compared and combined, in particular within fields concerned with human-technological interaction[5]. Research using one approach can also expose weaknesses in and/or give indications of a necessity of further research using a different approach.

The motivations for choosing a qualitative approach were based on the scope of the thesis. To conduct large scale quantitative studies and surveys of several types of maker communities and people engaged in the development of open concepts-based digital fabrication, and to develop relationships with key people in significant projects in order to obtain non-public statistical data, I estimated a required time frame on the order of several months to gather datasets comprehensive and non-biased enough to be reliable. In accordance with my philosophy as detailed above, I would also feel the need for complementary qualitative studies. For example, quantitative data mined from internet DIY communities would be well suited to map demographics, participation rates, how various factors have changed over time et cetera, whereas qualitative studies would be better suited to find answers to questions of *why*; why people participate, why demographics look such and such, and so forth. I concluded that an initial qualitative meta-study would show if there

[4]See for example Dahlbom and Mathiassen (1993), and Pirsig (1999) for a philosophical discussion.
[5]See Avison and Fitzgerald (ch. 28.3, 2006) for a comparison of methodological approaches in the context of development of human-computer interactive information systems.

is, to begin with, a need for such larger quantitative and/or qualitative studies; in which areas; and which particular questions are of interest. I consider this thesis a pre-study of a poorly understood field.

The research of this thesis has been conducted as a literature study of extant published peer-reviewed studies and articles concerned with the realms of open source, open source hardware, home fabrication of physical goods, DIY, crafting, and maker culture. Some information has been gained from non-reviewed sources where deemed justifiable by their nature, such as definitions of open source and free software retrieved from the Open Source Initiative and Free Software Foundation respectively, the authority of whom on those matters should by now be well accepted and established as common knowledge. In some cases where relevant, official press releases are cited on merit of being primary sources. Likewise, the nature of web-based projects and -communities means that sometimes the only information available on certain topics is volatile and difficult to verify, often presented in the form of FAQs and user-editable wikis. While such sources would traditionally be ill-suited in a scientific context, I have made the judgement that it would be impossible to examine such communities without referring to material of that nature. Typically, however, any such information used herein is primarily descriptive and exemplifying of some aspect of the community itself such as it is presented to its participants.

In total, some 90 articles from the ACM Digital Library, IEEE Xplore Digital Library and Elsevier Science Direct were selected for review, of which over 30 were deemed relevant for direct inclusion. Keywords used included, but were not limited to, "open source", "open source hardware", "DIY", "open design", "3d printing", "home production", "commons-based peer production", "arduino", "raspberry pi", "reprap", "participatory design", "hacking", "digital fabrication", and variations and permutations thereof. Additional keywords such as "democratization", "feminist", "gender", "developing world" and others were also used in combination.

Based on abstracts, articles were clustered into a number of categories including Open Source, Open Hardware, Digital Fabrication, 3D Printing, Home Fabrication, Demography, Democratization, Arduino, Raspberry Pi, RepRap, Collaboration, DIY, and Maker Culture. This was done using tags in a reference manager, as it allowed for both fine-grained sorting as well as umbrella categories. It also allowed for an overview of where there was cross-over between articles with differing primary foci. After an initial reading, tags were reviewed, added, or removed.

Articles were selected for inclusion primarily based on their scope; that is, how well they related to the wider topic of this thesis. For example, an article with a singular focus on the technical process of 3D printing was not included, neither were for example articles dealing with open source or collaboration in more traditional contexts of software development. The selection was also based on how well the articles complemented (but *not* on how well they reinforced) each other in trying to provide an overview of the topic for this thesis.

Potential weaknesses of my methodology are the inherent risks of selection bias and unconscious self-reinforcement; insufficient selections (especially within the somewhat limited timeframe of a Bachelor's thesis); the risk of accidental omission of significant studies[6]; and also that of the results of a literature study only being as reliable as the studied material (unless the results are that the literature itself is unreliable).

4. Results

4.1 Open Source Hardware platforms

In my research I have found that three platforms in particular have made an impact on digital fabrication; the Arduino microcontroller, the Raspberry Pi single-board computer, and the RepRap 3D printer. They are by no means the only commonly used products of their type, but their significance and impact make them suitable to serve as ideal representatives of each respective category. For the most part, any mention of the Arduino, the Raspberry Pi, or the RepRap, could be amended with "or equivalent device".

4.1.1 The Arduino microcontroller board

A microcontroller is a small computer consisting of an integrated circuit with a processor, memory, and input/output interfaces, typically designed for use in embedded systems. The Arduino microcontroller project was created in 2005 as an inexpensive tool for hobbyist, educational, and professional use. Originally available only from the Arduino on-line store, it is now also available from mainstream retailers both on-line and in brick-and-mortar stores. In 2013 an estimated 700 000 official boards had been registered, with an additional estimation of at least one derivative or clone per every official board (Arduino Foundation, 2013).

An Arduino board typically consists of an 8-, 16-, or 32-bit Atmel AVR or ARM processor; analogue and digital input/output pins; serial communication interfaces; and sometimes an USB connector. The I/O pins provide an interface to other hardware, such as sensors; touchscreens; bluetooth interfaces; extension boards; or any number of other hardware. The serial interface (including serial over USB) provides a means for loading software onto the Arduino from a computer. There exists a large number of official Arduino variations, as well as myriad third-party clones and derivatives of the different variations[7].

According to the Arduino Foundation[8], the Arduino programming language is an implementation of Wiring, a similar physical computing platform, which is based on the Processing multimedia programming environment. The Arduino language resembles C/C++, and can be extended with C/C++ libraries. While C/C++ are often considered more difficult languages for beginners compared to, for example, Java or scripting languages such as Python, Arduino code can often be kept quite simple and straightforward thanks to libraries for many common tasks. The Arduino Foundation website contains API documentation of the Arduino language; a list and documentation of official libraries included in the Arduino IDE; as well as a list of community-contributed code snippets, sketches, libraries, and tutorials. Any language that supports serial communication can be used for interfacing with

[6]A good example here is the RepRap study by de Bruijn (2010), which was discovered late in the process. It did, however, turn out to support the findings of other literature included in my research.
[7]See for example *Collaborations in Open-Source Hardware: Third Party Variations on the Arduino Duemilanove* (Mellis, 2012) and *LilyPad in the Wild: How Hardware's Long Tail is Supporting New Engineering and Design Communities* (Buechley & Hill, 2010)
[8]http://arduino.cc

the Arduino, but the Python scripting language, especially with the pySerial library, has become particularly popular. The Arduino Foundation provides an official (if somewhat rudimentary, lacking code completion and syntax highlighting) integrated development environment (IDE) to ease Arduino development and deployment of code. Use of the IDE is not necessary, however, with one alternative being the Ino commandline toolkit[9] for Linux and OSX. Ino can be used in conjunction with any text editor, such as Vim or Emacs, or be integrated into a third-party IDE.

4.1.2 The Raspberry Pi single-board computer

A single-board computer is similar to a microcontroller in concept; a circuitboard with one or several processors, memory and input/output interfaces. Unlike a microcontroller, single-board computers are typically more powerful and often come with the interfaces expected of a regular desktop computer, i.e. ethernet, USB, audio and video outputs. Unlike a desktop computer, single-board computers typically do not have expansion slots; rather, components such as the processor and RAM are soldered onto the board. Single-board computers are usually less powerful than an average desktop computer, but can be powerful enough to serve as one.

The Raspberry Pi, from here on referred to as RPi, is a single-board, ARM-based computer. It was first launched in February 2012, and by now over five million units have been sold according to the Raspberry Pi Foundation ("FIVE MILLION SOLD!", n.d.). It is currently available in three versions: The Model A+, typically priced at $20 with a 700MHz ARM1176JZFS single-core processor and 256MB RAM; the Model B+, typically priced at $30 with an additional 256MB RAM for a total of 512MB and various other improvements; and the Raspberry Pi 2 Model B at $35, featuring a 900MHz quad-core ARM Cortex-A7 processor and 1GB RAM. All three versions feature a dedicated GPU capable of decoding 1080p HD video; HDMI, audio, ethernet and USB port(s); microSD card reader for the operating system and storage; on-board connectors for a serial display, camera add-on, and 40-pin general purpose input/output (GPIO) headers. The RPi CPUs are also capable of quite significant overclocking without voiding the warranty or requiring additional heatsinks. Operating systems compatible with the RPi include (but are not limited to) several versions of GNU/Linux, FreeBSD, Windows 10, and RISC OS. Like with the Arduino, various third party shields are available, offering special features without the need for soldering. Unlike the Arduino, which is best suited as a controller of other hardware and peripherals through its GPIO pins, the more powerful and capable RPi is also often used as-is, running software that utilizes its network, audio/video and USB interfaces to communicate with other discrete devices. Programming for the RPi can be done in any common language or environment, as the RPi, unlike the Arduino, is a regular computer, albeit in a very small form factor.

4.1.3 The RepRap 3D printer

Version 1.0 of the Rep Rap 3D printer, codenamed "Darwin", was released in 2007[10] and originally developed as a self-manufactured kinetic machine; that is, a machine with the capability of self-reproduction through manufacture of parts, or a copy, of itself (Jones et al.,

[9] http://inotool.org
[10] http://reprap.org/wiki/RepRap_Family_Tree

2011). It is marketed as "humanity's first general-purpose self-replicating manufacturing machine".[11] RepRap is a free/libre OSHW platform released under an amended version of the GNU General Public Licence[12], with electronics built on the Arduino platform.

Contrary to the design of most practical artificial producers that start with proposed solutions to the technical difficulties of getting a kinematic machine to copy itself, Jones et al. (2011) state, "RepRap was instigated by biomimetically considering extant naturally evolved *strategies* for reproduction". This biologically-driven perspective also led to the decision of releasing RepRap as open source hardware. Jones et al. (2011) compare to the reproduction of flowers, pointing out how there is no biological "copywriting" of the "intellectual property" of their genome. The intent of the flower, like that of RepRap, is to proliferate and spread itself as easily as possible.

> *"For this reason, it was decided to follow the principles of the free software movement and to distribute every piece of information required to build RepRap under a* software libre *licence that requires no royalty payments whatsoever. This would allow private individuals to own the machine, and to use it freely to make copies for their friends"* (p. 180)

With the exception of some metal parts and electronics, RepRap is capable of fabricating most of its own components. A decision was made during the design process, that all parts that the RepRap cannot reproduce itself "had to be cheaply and widely available to maximise the ease—and hence probability—of reproduction" (Jones et al., 2011). RepRap is currently in its fourth generation. Based on 3D model files, RepRap uses a technique known as Fused-filament Fabrication (FFF), or sometimes as Fused Deposition Modelling (FDM) to produce components from a variety of thermoplastic polymers (Jones et al., 2011). In addition to the official RepRap product, there exists a large number of alternative third-party designs based on, and modified from, the RepRap design.

At the time of this writing, the official RepRap wiki lists and links to 52 sites (a small number of which being reported as dead or down) containing resources in the form of 3D model files. Out of the 18 sites where the conditions for uploading are listed, 14 require registration, one allows free uploads (as in unlimited and "no-strings-attached", requiring neither registration nor a fee), while three have a mix of conditions (that may include a fee). 21 sites list the conditions for downloads, out of which 15 are marked as free, one requires registration, and five have mixed conditions. 13 of the sites list the licensing options available to contributors of the site, most of which offer several or partially listed options making an exact breakdown in numbers difficult. Typically, options offered include a combination of open source licenses such as the Creative Commons family of licenses, versions of the GNU General Public License, or the BSD License, but commercial options may also be available. While some sites offer model files for any type of production, and sometimes additional resources such a tutorials and community functions, other have a clear focus. Examples

[11]http://reprap.org
[12]http://reprap.org/wiki/RepRapGPLLicence

include musical instruments[13]; anatomical, biological, and labware models[14]; fabrication machines such as 3D printers, CNC mills and laser cutters[15]; and sex toy designs[16].

4.2 Maker platforms

In addition to physical meeting places and communities for technical and non-technical DIY, such as Maker Faires (Dougherty, 2012) and hackerspaces (Fox et al., 2015), many internet-based platforms exist and serve as hubs for collaboration, resource-repositories and sharing, discussion, exchange of ideas and so on. These can be very large, with hundreds of thousands of users (Kuznetsov & Paulos, 2010) and myriad projects, with wide or narrow foci. See for example the collection of links on the RepRap wiki mentioned in the previous chapter. Instructables.com detailed in the next chapter is one of the largest and most popular.

4.2.1 Instructables.com

To represent maker culture and peer production practices in the context of open concepts-based digital fabrication, I have chosen Instructables.com, launched in 2005, as it contains a large number of aspects relative to maker culture in general, and open production of consumer electronics in particular. Instructables were acquired by Autodesk, Inc., known for the AutoCAD computer aided design (CAD) software, on August 1 of 2011 (BusinessWire, 2011). Content topics on Instructables is divided into six categories: technology, workshop, living, food, play, and outside. These are not exclusive and may overlap, for example in the form of instructions on how to build an Arduino-based sous-vide cooker.

Instructables provides community and social features such as moderated user-created special-interest groups that users can join or follow; discussion forums for a number of categories; and a question/answer feature similar to Answers.com. Read access requires no registration, but participation does. Registered users have the ability to create and upload "instructables", that is, design documents; photographs; assembly instructions; source code; and other resources for others to use. Registered users can also create collections of their favourite instructables, which can be added to by clicking a button while browsing the site, similar to favourites and playlists on sites like YouTube. There also exist apps for Android and iOS to aid mobile participation. The features available to users are too many to mention, but in general it can be said that they include everything that has come to be expected from a modern community website in terms of social interaction.

Registered users have the ability to create a public profile with standard (optional) personal information such as age, gender, geographical location, contact information, and more. In addition, there is the option to set a default licence for published instructables. The licences available provide varying degrees of restrictions, openness and freedom, ranging from Public Domain (no copyright), through a number of free/libre/open source licenses[17], to All Rights Reserved (full copyright). Since June 2009, Instructables.com somewhat controversially offer a "Pro" membership to unlock certain futures that previously free, in

[13]http://3dprintedinstruments.wikidot.com
[14]http://3dprint.nih.gov
[15]http://www.openbuilds.com
[16]http://www.makerlove.com
[17]At the time of this writing they are: the Apache Licence, the GPL and LGPL, and all six current Creative Commons licenses.

addition to some new features. Pro features include the ability to download instructables in PDF and eBook format; fewer ads; discounts from vendors partnering with Instructables; the ability to view all steps of an instructable on one page; and the ability to make uploaded instructables private, visible only to select users.

During the research for this thesis, an inquiry was made to Instructables for any statistical data they might be able to share, but while accomodating, they were unable to comply.

4.3 Who are the makers?

Providing a clear image of the demographics of the maker culture of consumer electronics has proven somewhat difficult. While the overwhelming majority of makers of consumer electronics on the whole appear to be western and male, as will be exemplified later, there are some caveats to the results of prior research (as detailed in the next section), as well as indicators that there is a large user base *in potentia* as novel use of microcontrollers and single-board computers is being adopted by makers of previously non-technical artifacts. For future research "Who are the makers?" appears the less interesting question compared to "Who are becoming the makers?".

4.3.1 Gender

In a large-scale study of six online DIY communities[18], Kuznetsov & Paulos (2010) found that out of 2608 responses, 2287 respondents identified as female, 186 as male, and 11 as transgender. They note, however, that size differences between the communities in combination with different gender makeup of their respective user bases, as well as different levels of response rates may have skewed the results. Ravelry (300,000 members) and Craftster (170,000 members), communities focused on crafts such as knitting and crochetry, both have a significant female majority (71% and 68% respectively) userbase and a higher participation rate in the study than smaller communities such as Adafruit (8000 users) and Dorkbot (only mentioned as having "sixty six active chapters" consisting of groups of people who meet in person), which are geared towards electronics. Kuznetsov & Paulos (2010) further note that Instructables, being the largest community in the study at 500,000 members, had a relatively low response rate. As the study included communities with a non-technical focus, it is debatable to what extent it applies to the consumer electronics focus of this thesis.

There are, however, interesting parallels to two studies performed by Buechley & Hill (2010) comparing the gender makeup of customers and builders of the Arduino and LilyPad (a very small Arduino variant designed to enable the creation of electronic textiles) platforms. While the authors acknowledge limitations in their analysis and the underlying dataset, a clear trend could be seen. 88% of customers purchased Arduinos; 9% purchased LilyPads; and 3% purchased both. 78% of customers who purchased Arduinos were recorded as male, and 9% were female, while the remainder could not be classified. 86% of Arduino projects in the study were done by males, and only 2% by females. Conversely, only 25% of LilyPad projects were done by males and a majority 65% by females. Further, a study of feminist hackerspaces by Fox et al. (2015) also took note of the inclusion of textile-working

[18]http://instructables.com, http://dorkbot.org, http://adafruit.com, http://ravelry.com, http://craftster.org, and http://etsy.com

tools juxtaposed with common hardware hacking tools and a "merging of hackerspace activities with careful craftwork" that "suggests an intentional entanglement of hacking and practices traditionally associated with women". Buechley & Hill (2010) suggest that the gender imbalance in traditional engineering communities may not be a consequence of prejudice or exlusiveness, but due to being culturally and intellectually limited in breadth. Supported by Weinberger (2004), Buechley & Hill (2010) maintain that the lack of participation in STEM (science, technology, engineering, and research) communities by women and minorities is not due to being intimidated or unqualified, but rather from being uninterested. All articles cited in this section imply directly or by inference that the participation of women in the creation of technological artifacts increases when there is a cross-over between technology and other crafts and hobbies.

4.3.2 Nationality and ethnicity

The reviewed literature in general suggests an overrepresentation of individuals from the English-speaking developed world, but I have determined the level to which surveys at all include groups of communities outside of said sphere to be either inadequate or unclear. It is therefore not possible to present any reliable results on this matter. What can be said is that motivations and expressions of the DIY manufacture of consumer electronics differ to some extent between the developed and developing nations (Tanenbaum et al., 2013), and also that previous efforts of introducing low-cost computing has yet to gain a foothold in developing nations, but it remains to be seen whether the RPi can succeed as an alternative where other solutions have failed or falter (Heeks et al., 2013).

4.3.3 Age and educational background

I have found the sample sizes in the reviewed literature where age and/or level of education is included in surveys to be too small, or too affected by selection bias, to produce meaningful results in the wider context of this thesis. An overrepresentation of individuals with a background of higher education in technological fields is suggested, but I have deemed the data too limited and unreliable for inclusion.

4.3.4 Motivations

A number of motivations for the participation and engagement in open-concepts based digital production (and DIY in general) appear in the reviewed literature. In a survey by Buechley & Perner-Wilson (2012)[19], interviewing crafters in the areas of painting, sewing, carving, and building electronics, recurring themes are noted as S*haring, Aesthetics, Peacefulness, Ideas,* and *Personal use*. Buechley & Perner-Wilson (2012) found that enjoyment of the process and affection for the outcome was shared among participants in all areas. 40% of painters, carvers, and sewers, and 20% of electronics makers[20] mentioned sharing of their work to be important. Tanenbaum et al. (2013), in studies of Steampunk

[19]Albeit small, with only ten participants from each field. 65% reported as male, 35% female. 65% of whom were from the US, 30% from India, and 5% from Europe (Buechley & Perner-Wilson, 2012)
[20]The low percentage of electronics makers reporting sharing as important is surprising considering the emergence of open source culture from the technical community. This could possibly be explained by the small sample size. Compare to the larger survey of Kuznetsov & Paulos (2010), although it had other issues with uneven representation of respondent groups (notably a low number from the technical communities and less than 10% of respondents reporting as male).

Makers, Thai crafters, and interviews with hobbyists and professional programmers, identify three core concerns behind people's engagementent in DIY and crafting; *Pleasure, Utility*, and *Expressiveness*. Tanenbaum et al. (2013) also stress a philosophical-political drive:

> *"DIY practice is a form of nonviolent resistance: a collection of personal revolts against the hegemonic structures of mass production in the industrialized world. The fact that Makers rely upon these same structures to engage and disseminate these practices complicates, but does not negate, their revolutionary nature."* (p. 2609)

In his Master's thesis on the RepRap project, de Bruijn (2010) includes a literature review focusing on the motivations of individuals to collaborate and participate in communities such as open-source projects. Proposed are motivations such as *Autonomy*, *Striving for competence, Relatedness,* and *Meaning*. In the previously mentioned study by Kuznetsov & Paulos (2010), 97% of participants work on DIY projects to "Express myself/be creative", with over 68% strongly agreeing to the statement. 52% agreed with their motivation being to "Learn new skills", 39% strongly agreed. To "Gain internet fame or reputation" (70% disagreeing) and "Make money" (25% disagreeing, 15% disagreeing strongly) were the least and second least popular reasons. 40% of participants contribute to DIY *projects* to work/spend time with friends, while 80% of respondents contribute to DIY *communities* to meet people with similar interests. 90% of participants share at least some of their projects with the community, with more than 50% stating lack of time as the reason for not sharing.

The terminology and exact definitions vary by author, but for all intents and purposes the results are the same: personal enjoyment, personal development, freedom of expression and freedom to do what they want with the hardware, an outlet for creativity, social interaction, personalization of artifacts, an emotional and/or political attachment to the project, and the innovation and creation of practically useful or needed artifacts. If reduced to their essence, the primary motivations appear to be "because I can and want to". Pleasure and enjoyment appear to be particularly ubiquitous motivations, but Tanenbaum et al. (2013) find that all of these various motivations are often addressed simultaneously, further arguing that it questions widespread assumptions on the dichotomy between work and leisure. This appears to be in line with Fox' (2014) definition of Third Wave DIY, and Dougherty's (2012) description of maker culture[21].

Despite the very individual-centered and non-commercial motivations, and their definition of DIY participation as revolutionary, Tanenbaum et al. (2013) note an increased corporate and governmental interest in the maker movement, citing entities such as General Electrics, Microsoft, Google, and Intel sponsoring Maker Faires in Africa and the United States, and the Obama administration funding STEM education and a 3D printing research center. The acquisition of Instructables.com by Autodesk Inc[22], is another example, as is MakerBot Industries moving from an open model towards increasingly closed and proprietary hardware and software (MakerBot, 2012).

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[21]See chapter 2.6
[22]See chapter 4.2.1

Further diversifying the motivations are DIY practices in developing nations. There, DIY electronics appears as a hybrid of Third Wave DIY and First Wave (subsistence) DIY as defined by Fox (2014). Examples given by Tanenbaum et al. (2013) of DIY electronics in developing nations, such as disaster relief or as a source of income, appear rather utility-driven, yet still with a strong streak of expressiveness and pleasure.

4.4 Applications of Open Source Hardware and Digital Fabrication

The application of open source hardware appears virtually endless in diversity; it can be found in many disciplines of science and research, in craft, in music, in disaster relief, education, curios and novelties, as physical aids and human interface controllers, and any number of other areas. In the academic literature, most attention is directed towards research and scientific application, and the normally prominent elements of playfulness and expressiveness are thus less pronounced in such examples, as is the crossover wwith traditional crafts. As is evident by visiting digital fabrication and maker communities such as Instructables, the vast majority of projects are, however, for more personal use where the motivations outlined in chapter 4.3.2 better apply.

Buechley & Hill (2010) describe the integration of Arduino-based LilyPad controllers with traditional textile crafts. Al-Haija et al. (2014) outline an RSA cryptosystem for small scale networks, implemented with an Arduino Mega2560R3 and peripherals such as keypads and an LCD touchscreen. Augmented with a small solar cell they consider it useful for the use in wireless sensor networks. Ferdoush & Li (2014) detail a wireless sensor network system using an RPi, an Arduino, and a ZigBee radio transceiver in combination with temperature and humidity sensors. Jadud et al. (2014) provide a proof-of-concept of an affordable Arduino-based system of sensors for monitoring air quality in low- to medium-income homes. Krishnan et al. (2014) designed a soccer-playing robot by mounting an RPi with a camera attachment to a humanoid Bioloid Premium robot built from a ready-to-assemble kit[23]. Teikari et al. (2012) created an Arduino-based LED stimulator system for vision research and demonstrates its application in murine pupillometry, rodent models for cognitive research, and heterochromatic flicker photometry in human psychophysics. Kornuta et al. (2012) detail an OSHW platform for the study of lymphatic biomechanics *in vitro*. An Arduino Uno is used to provide open-loop control of a digital peristaltic pump using precisely timed serial commands. Varesano (2013a; 2013b) describes their work on LibreMote, a framework consisting of an OSHW Arduino-compatible board, programming libraries, and Digital Fabrication models of controllers based on the framework. Varesano (2013b) also describes their FreeIMU framework of a sensor board built on top of the Arduino platform. Ausareny et al. (2014) use Arduino based OSHW to merge emergent scientific practices such as microfluids and biochips with traditional crafts to create a prototype of what they call a "Wayang kulit microfluidic shadow theater". Magnetic particles and zooplankton are used to simulate a traditional Indonesian wayang kulit puppet show. Mellis & Buechley (2012a) and Mellis et al. (2011) describe their experience with workshops

[23]Compare to the Pepsi-sponsored Sound of Football project (http://ourwork.se/thesoundoffootball). Unfortunately, the project site (http://thesoundoffootball.com) appears defunct as of May 2015.

where users would construct and/or personalize artifacts such as an FM radio or a computer mouse, which also showed a merger of craft and electronics. Capurso et al. (2014) propose a vehicular accident detection system built with an RPi, Texas Instruments SensorTags, and a smartphone application running on the open-source based Android operating system. Faugel & Bobkov (2013) describe the use of OSHW such as the Arduino for use as interfaces to, or replacement of, difficult to find, out-out-production components to keep old hardware running. Malinen et al. (2010) outline eCars - Now!, a community with the goal to convert internal combution engine cars into electric cars using OSS and OSHW means. Heeks et al. (2013) describe the use of RPi computers for education in developing nations, replacing conventional desktop computers. The examples are endless.

4.5 Prerequisites for an emergent paradigm

Internet access appears as the great facilitator in terms of providing a practical infrastructure, as are open source concepts in terms of creating an environment of openness, availability and sharing. While I have not found any studies that explicity show this, it can be inferred by their ubiquitous appearance in literature concerning maker culture and DIY electronics[24]. The internet as infrastructure is simply taken for granted, as it often is in general in the developed world. Web 2.0[25] fundamentals appear as a large part in facilitating the kind of communities and practices observed.

The prevalent use of open hardware and -software platforms, and why, is rarely discussed on its merits of being open (outside of economical motivations); it rather appears as the default. Arduino, RPi, RepRap, and equivalent products consistently appear throughout the reviewed literature and in maker communities such as Instructables. As these are results arrived at through inference rather than empirical study, they should be viewed as a strong indicator and incentive for further research rather than evidence in and of itself.

5. Discussion

The nature of this study is such that it does not necessarily give conclusive answers to the questions initially asked. What does the landscape look like? Diverse. Which are its defining features? To some extent context-dependant. How does it manifest? In many forms. The answers are vague. With more time, the selection of articles could have been larger, but from the abstracts of the many articles that were not selected for inclusion in my research, their scope was deemed to be similar to those that were. I believe that there is a strong argument to be had for the notion that proper scope is what is lacking in extant research into this new paradigm. Sample sizes in studies are too small or show bias due to disproportionate selections or participation among various demographics. Insufficient consideration of language barriers makes research into open concepts-based digital fabrication in the developing world and other areas outside of the English-speaking sphere inadequate, as it

[24]de Bruijn (2010) comes to a similar conclusion in his study of the RepRap project on the viability of the open source development model for digital fabrication, but notes that his study is limited to a single project and thus cannot be assumed to be representative.

[25]See Tim O'Reilly, *What is Web 2.0* (2009) and O'Reilly & Battelle, *Web Squared: Web 2.0 five years later* (2009)

becomes invisible to researchers. It is for example not unreasonable to assume a vibrant Japanese community[26] based on a traditional affinity for technology, yet is was entirely absent in the literature reviewed. While the reviewed surveys that included gender data suffered some of the same problems that made me decline to present any results relating to other demographic factors, I believe they provided important insights and hints of the motivations of women engaging in electronics fabrication, paths to stimulate further engagement, and the merger of traditional crafts and electronics. An important omission in this thesis was that of crowdsourcing and crowdfunding; an increasingly popular way for individuals and smaller companies to find funding for any kind of producs and projects—in particular those perceived as having a limited target demographic and/or being too niche for traditional investors to show interest. This omission was made partly due to time constraints, partly due to being a new phenomenon that is less studied than OSS and maker culture/DIY, in particular with a specific focus on electronics.

I do believe the study serves its purpose despite these weaknesses, however, as the overarching question is just as much that of whether there is adequate research into this phenomenon, trend, movement, culture or paradigm—pick a word—to understand it to begin with. I believe that the vagueness of my results has shown that there is sufficient variation in motives and application; indications of an—if slowly—emerging demographics change; and deviation from established concepts such as open source, open hardware, open design, commons-based peer production, and maker culture; to say that it is not a such or such phenomenon. Rather it is an emergent paradigm shift in culture, technology, crafting, economics, and many other areas. In failing to provide a comprehensive image of a phenomenon with a clear demographic, ideology, motivations and drive, I have succeeded in showing that it is something larger, and as such must be approached differently. I believe a larger study, such as a doctoral thesis, would be warranted to better understand this paradigm and create a proper framework for future research. The natural starting point I suggest, is a thorough study of communities such as Instructables, that in many ways embodies this paradigm through its inclusion of both open concepts and well as divergences, and also showcases much of the crossover—or rather merging—of electronics and other crafts. Instructables and similar communities do have the bias of belonging to the English-speaking cultural sphere, but should nevertheless be able to produce a very useful dataset to work with. The merger of digital fabrication with craft appears throughout the reviewed literature; in particular in the works of Leah Buechley, David Mellis, and their collaborators[27], whom have taken an explicit look at the relationship between craft and digital fabrication. This relationship appears as a significant factor in the commodization and democratization of technology and a driving factor in this paradigm shift, and should be examined more closely. I believe that one of the most interesting fields of study should be the emergent demographics; the potential for a large increase of women participating in digital fabrication has been outlined in previous chapters, whereas Eisenberg (2013) discusses the potential of 3D printing for children, to give two examples. Lipson & Kurman provide an

[26]Particularly robot making appears to be popular in Japan.
[27]See for example Buechley & Perner-Wilson (2012), Zoran & Buechley (2013), Mellis & Buechley (2012a; 2012b), and Mellis et al. (2011)

insightful speculative view on the current and future opportunities and possibilities presented by 3D printing and its place in an emergent economy in *Fabricated: The New World of 3D Printing* (2013). Their book is in concordance with the themes observed in my research, and should also serve as suitable inspiration for further work.

6. Conclusions

With this thesis I set out to answer one major and two sub-questions, and where the answers lack in satisfaction, they are abuntant with intrigue. As discussed in the previous chapter, the landscape of open-concepts based digital production has been shown to be both varied and expanding, and could very well be significantly different in five or ten years. Likewise, the main defining feature is that of versatility and dynamism. Open- and libre practices are common, as are elements of participatory design, and the merger of craft and technology, but they can scarcely be said to be defining due to the commonality of deviations. Third, the answer to the question of how open concepts-based digital fabrication manifests turned out to be "in any way imaginable".

My two primary conclusions are those of an emergent paradigm, and a lack of sufficient research of its components viewed as parts or a greater whole. What we are seeing is something that emerges as post-open source, post-Web 2.0, and post-commodization of technology. It is not necessarily fully formed, and neither does the post- prefix imply that former concepts are abandoned, but rather that we are approaching the consequences of their convergence and mainstream appropriation. As seen with Instructables for example, open concepts are an intrinsic part and prerequisite of the culture and practice, but its members and participants are not necessarily ideologically invested. Rather they are eating the fruits grown by decades of open source activism and technological advancement, and they are free to choose how much, and of which fruits, to eat.

I originally set out to examine digital fabrication of consumer electronics as "an open source thing", but it quickly became obvious that while OSS and OSHW were everywhere, it was not "an open source thing". It was rarely *about* open source. Neither was it always *about* technology and electronics; rather, electronics were *included* into other things. In fact, the most difficult part of this thesis was to figure out what to call it. Open concepts are absolutely intrinsic to this paradigm, yet rarely—if ever—were the motivations of participants in the production of open concepts-based digital production those of the Stallmans or Raymonds of the world. Rather than rights and freedoms or belief in a development model, it turned out to be about expression and enjoyment and possibilities. "Because I can and want to". For commercial entities engaging, it also appears to be due to a measure of foresight and an awareness of a changing market. Concepts like ubiquitous computing, internet of things, and wearable computing also appear as influencing factors.

What do we call this paradigm, and what will it look like five or ten years from now?

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