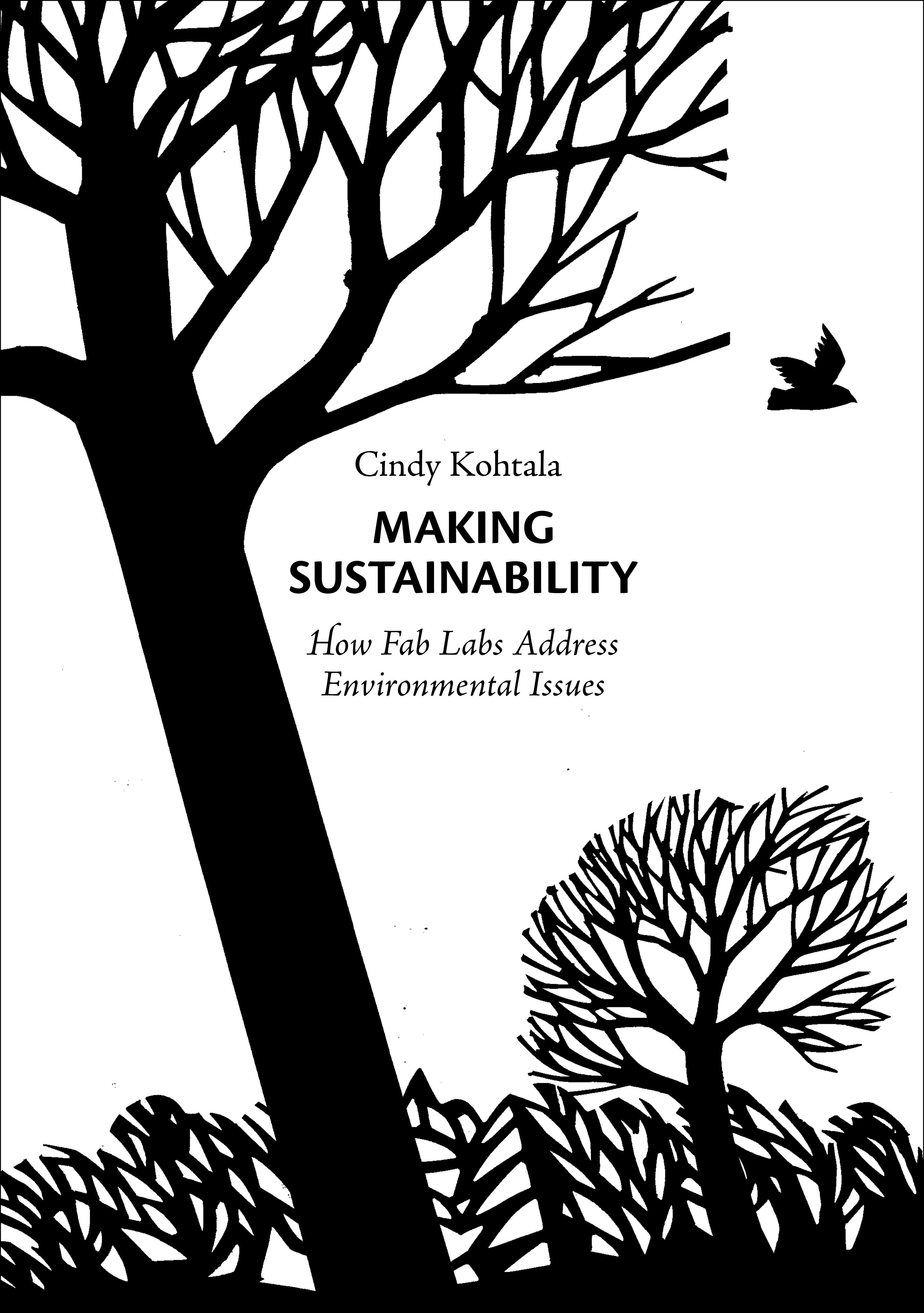
Cindy Kohtala

MAKING SUSTAINABILITY

How Fab Labs Address Environmental Issues

Aalto University



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ABSTRACT

Digital manufacturing technologies are proliferating and can enable socially significant, innovative new forms of production and consumption. This thesis examines the environmental sustainability issues in peer production and how they are addressed in Fab Labs (fabrication laboratories): shared spaces where users can design and make their own artefacts outside of conventional mass production channels, using, for example, laser cutters, 3D printers and electronics stations. Fab Labs are open to members of the general public, who learn to use the equipment themselves and are encouraged (or required) to document and openly share their projects. 'Making' in Fab Labs and the 'maker movement' are often endorsed by proponents as a better alternative to mass consumption and consumerism, whether through enhancing skills to build and repair, answering one's own needs as opposed to 'satisficing' through passive consumption, or distributing production within local networks as opposed to long, transport-intensive and large-volume supply chains. However, Fab Labs and makerspaces are contexts rife with paradox and complexity concerning appropriate use of materials and energy. Little empirical research on material peer production currently exists, and the environmental impacts, and benefits, of digital fabrication are largely unknown.

Primarily through ethnographic research methods and Symbolic Interactionist analysis, the thesis examines daily practices and discourses in selected Fab Labs and how sustainability is represented in these communities. The findings articulate how the actors' interactions, expressed intents and contextual conditions serve to shape the Fab Lab. The key finding is the conflict actors encounter between – on the one hand – setting ambitions, promoting particular ideologies and espousing sustainability-oriented

values, and – on the other hand – realizing and enacting these values in the mundane and constraining routines of everyday practice. Even actors with a clear ecological mandate struggle to engage with emerging sustainability issues in a rapidly changing sociotechnical environment. Present topics of concern and everyday tasks overshadow future strategy and vision work as well as engagement with environmental issues and rapid technology developments. However, actors who consciously and visibly strive to enact the espoused Fab Lab ideology, i.e. offering access to empowering, distributed technologies that enable people to meet their own local needs by design, appear better able to identify and tackle the environmental sustainability issues as they arise. Environmental issues are also intertwined with and embedded in other ideological concerns, but they are rarely promoted in their own right.

The thesis also details the current landscape of research literature on distributed production, who is studying these environmental issues and how, and the potential opportunities and threats in this new mode of production. The thesis thereby contributes to research on peer production communities, social shaping of technology and sustainable design. Knowledge of current maker practices and their sustainability implications have value for the peer communities studied, but also potentially technology developers and policy makers. As Fab Labs are experimental spaces for new digital manufacturing capabilities and activities, the wider implications of the findings may indicate how increasing digitalization and citizen involvement in production will transform design and production – and the sustainability implications therein.

Keywords: Fab Labs, environmental sustainability, digital fabrication, distributed production, peer production

A 'fixer' at a repair event held in the Helsinki City Library makerspace, Finland, in January 2014, organized by the non-profit arts organization Pixelache. Source: author.

LIST OF PUBLICATIONS

The dissertation includes the following original research papers.

PAPER 1.
Kohtala, C., 2015. Addressing sustainability in research on distributed production: an integrated literature review. Journal of Cleaner Production 106, 654-668. doi:10.1016/j.jclepro.2014.09.039

PAPER 2.
Kohtala, C., Hyysalo, S., 2015. Anticipated environmental sustainability of personal fabrication. Journal of Cleaner Production 99, 333–344. doi:10.1016/j.jclepro.2015.02.093

PAPER 3.
Kohtala, C., Bosqué, C., 2014. The Story of MIT-Fablab Norway: Community Embedding of Peer Production. Journal of Peer Production 5. http://peerproduction.net/issues/issue-5-shared-machine-shops/peer-reviewed-articles/the-story-of-mit-fablab-norway-community-embedding-of-peer-production/

PAPER 4.
Kohtala, C. Making 'Making' Critical: How Sustainability is Constituted in Fab Lab Ideology.
Unpublished, in review.

AUTHOR'S CONTRIBUTIONS

PAPER 1: SOLE AUTHOR

The paper presents the construct of "distributed production" and an integrated literature review on such distributed practices where citizens have a stronger role in the design and production of goods. The literature review spanned the contents scope from mass customization of goods to peer production of material artefacts and identified the issues on which researchers interested in the environmental sustainability potential of distributed production focus. The article summarized the environmental benefits of distributed production as highlighted in the literature and proposed potential negative impacts that were little or not addressed.

PAPER 2: MAIN AUTHOR

The paper presents the results of a participatory workshop where active practitioners and experts in peer production, peer learning and open innovation were guided through tasks to identify key trends and solutions in future material peer production. The analysis focused on how sustainability was represented in the trends and solutions as discussed by the participants, to gauge their awareness of the environmental implications. The findings indicated that actors with competence and interest in advanced technological maker topics were not actors with competence and interest in environmental issues. As first author I was mainly responsible for the data analysis, writing up of the empirical sections and summarizing the key findings and their implications. The second author was responsible for the workshop design and the formulation of the property space matrix that served as the foundation for the data analysis, to which he also contributed.

PAPER 3: MAIN AUTHOR

The paper presents an ethnographically informed narrative on the historically important Fab Lab in northern Norway (being among the first established). Such a critical research site contributes to a better understanding of the role of people and place in a Fab Lab's identity, and how rhetoric and practice are aligned or conflict, especially over time. Common issues in Fab Labs are clearly apparent in this Lab and emphasized in this paper: the need for funding is a key barrier to enacting espoused ideologies, and Fab Labs may struggle to create identities in both the Fab Lab network and in their local communities. As first author, I was responsible for structuring the paper, identifying the key findings and their implications, and most of the writing. The second author contributed descriptive narratives on her key themes that I edited and integrated into the final article.

PAPER 4: SOLE AUTHOR

The paper presents a longitudinal ethnographic narrative on a northern European Fab Lab. Insights from other studied Labs and interviews support the conclusion that environmental sustainability is not a clear component of Fab Lab ideology but becomes intertwined with other issues. The paper articulates how the actors configured the space and materials collectively in pursuit of their goals; how materials in the Lab represented ideology; and how ideology was enacted or neglected in the course of everyday activities. The key findings present the opportunities and barriers for Fab Labs to take environmental sustainability into account actively in their everyday practices.

ABBREVIATIONS

CNC	computer numeric control
CBA	Center for Bits and Atoms
DIWO	do-it-with-others
DIY	do-it-yourself
FDM	fused deposition modelling
FLOSS	free/libre open source software
HCI	human computer interaction
IT	information technology
LCA	life cycle assessment
MIT	Massachusetts Institute of Technology
MSDS	material safety and data sheet
R&D	research and development
RSA	The Royal Society for the Encouragement of the Arts
SLA	stereolithography
STS	Science and Technology Studies
WELL	The Whole Earth 'Lectronic Link

LISTS OF FIGURES AND TABLES

ACKNOWLEDGEMENTS

Throughout this dissertation I stress how busy Fab Lab managers are. It is with some amazement, therefore, and no small amount of gratitude, that I acknowledge how so very generous my research subjects were with their time and ideas. Thank you.

To all the lovely folks at the European Fab Labs I visited, I warmly thank you and hope I can reciprocate in some way in future. Some of you not only put me up in your homes or Labs, you put up with me and my constant presence. To the anonymous Lab and the Waste-lab group who have the starring roles in this story (in paper 4), those people I cannot thank enough. You know who you are – I think you are heroes and adventurers.

There are also multitudes of people in the grassroots Helsinki maker scene as well as the Helsinki City Library with whom I had the privilege to speak. Sorry – you haven't seen the last of me, my audio recorder or my camera. Thanks to those of you who agreed to speak (or workshop) at my World Design Capital Maker Culture events, and thanks also to Agents of Alternatives for inviting me to write an essay on maker discourses for their compilation. Discussions with colleagues on email lists such as o2global, Open Design and Hardware Working Group and #sustmake have also been stimulating.

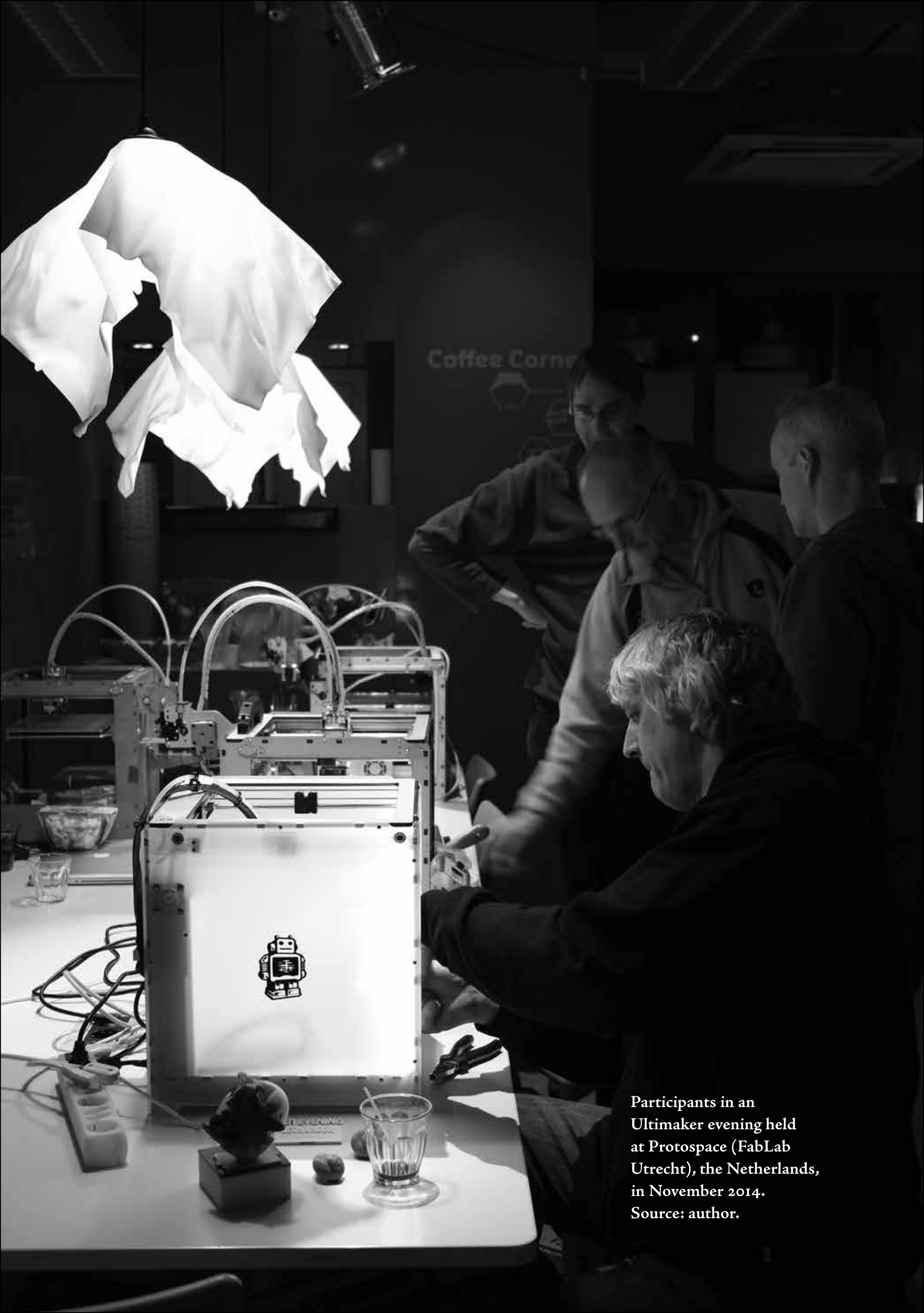
I am truly grateful to the Design Department for awarding me a three-year grant, which allowed me to pursue this research topic full-time with gusto from 2012. Thanks to a travel grant from Aalto ARTS I was able to conduct fieldwork and interviews at FAB10 in Barcelona, not only with Fab Lab managers and employees but also researchers, consultants and Fab Lab nomads. My research colleagues in the NODUS Sustainable Design Research Group kept me on my toes, as did colleagues and co-authors in

INUSE. My colleagues in Design Research also lent needed perspective and new insights in the courses and seminars in which I presented my work. My pre-examiners, Dr Peter Troxler and Dr Tere Vadén, provided superb commentary on the manuscript.

Alas, there is currently no body internationally that awards a Best Research Advisor In The World Prize; I will lobby for one to be given to Prof. Sampsa Hyysalo for his wise – and yet fun and funny – guidance, in what was at first the murky and mysterious waters of academia. Sampsa still best understands my fascination with the Fab Lab network – and why I see Fab Labs as highly important research subjects in view of building a more sustainable, more inclusive and more adaptable society.

To my parents, Viljo and Anja Kohtala, my sisters and their families in Canada, to my extended family in Finland, and my clever and wildly humorous friends in Helsinki, your support has been invaluable; your patience uncountable.

Cindy Kohtala
Helsinki, January 2016



Participants in an Ultimaker evening held at Protospace (FabLab Utrecht), the Netherlands, in November 2014. Source: author.

1

INTRODUCTION

Increasing numbers of citizens have access to digital fabrication equipment via devoted spaces known as Fab Labs, makerspaces and hackerspaces, which are mushrooming globally. Such access enables people to design and make their own products outside of conventional mass production and consumption channels, using technologies such as desktop additive manufacturing equipment (that is, '3D printers'), CNC (computer numeric control) milling machines, laser cutters, vinyl cutters and electronics stations for circuit prototyping. The technologies themselves, especially 3D printing, are widely espoused as disruptive technologies that will radically shift production and consumption patterns (Anderson, 2012; Marsh, 2012; Hamermesh, 2014).

The technologies are not new, as they have been used in industry, particularly in rapid prototyping, for decades; what is new is that costs of the equipment are rapidly decreasing, the machines are increasingly smaller and 'desktop', and the user base as well as use applications are expanding. Expiry of patents has especially fostered experiments in equipment design in open source development processes (de Bruijn, 2010; Jones et al., 2011), and users freely share and adapt designs and instructions for digital fabrication online (Kuznetsov and Paulos, 2010). Fab Labs, makerspaces and hackerspaces provide teaching and workshops to learn digital fabrication, but they also largely expect their users to use the equipment independently; this encourages peer learning and knowledge sharing. For explicit reasons such as 'empowerment', education and learning, and 'democratization' of production and technologies, Fab Labs are also expected to allow the general public access to their Labs at least part of the time, a mandate differentiating them from other makerspaces (Gershenfeld, 2005; 2012; Walter-Herrmann and Büching, 2013a). For Fab Lab founder Neil Gershenfeld, professor at Massachusetts Institute of Technology, 'makers' are "high-tech do-it-yourselfers who are democratizing access to the modern means to make things" (Gershenfeld, 2012, 48).

Disruptive technologies combined with new practices and values aligned with empowerment and peer learning means the Fab Lab model could well be a stepping stone to something new and different: more widespread implementations of distributed production, as an alternative to mass production. Many actors in the Fab Lab network and the 'maker movement' espouse personal fabrication as a clearly better alternative to mass consumption and consumerism. In Fab Labs the capacity to answer one's own needs locally, individually and as communities, is emphasized as a benefit (Gershenfeld, 2005), as opposed to being reliant on large corporate technology providers or 'satisficing' through passive consumption.[1] Other espoused benefits are the enhanced skills people acquire to build, disassemble and repair (Mellis and Buechley, 2014). These propositions have clear environmental implications, from lessened environmental impact resulting from production only according to need, to more eco-efficient use of materials and products combatting planned obsolescence, to reduced negative impacts from transport emissions. However, little empirical research exists to confirm whether these benefits are coming to fruition or even on what actually happens in these forerunner makerspaces.

1 'satisficing' here meaning settling for a consumer product that does not meet one's needs or expectations, after the term coined by Simon (1956)

Rifkin (2014), perhaps more than most commentators on Fab Labs or the maker movement, explicitly connects 'making' with environmental sustainability benefits: "The [Maker] Movement has been driven by four principles: the open-source sharing of new inventions, the promotion of a collaborative learning culture, a belief in community self-sufficiency, and a commitment to sustainable production practices" (Rifkin, 2014, n.p.). Rifkin's (2014) vision is of a more sustainable future world, where research and development (R&D) is distributed and democratized in Fab Labs and manufacturing is dispersed locally – powered by renewable energy, reducing transport emissions and eliminating the embodied energy in unneeded mass production intermediaries. Although stated as 'fact', Rifkin's four principles (which would help precipitate such a vision) remain propositions and assumptions. The maker movement itself as a community of communities is fragmented and does not necessarily sing with the same voice on matters of self-sufficiency and sustainable production. Moreover, reporting on the environmental sustainability of 3D printing, personal manufacturing or the maker movement in non-academic media has tended to be taken on by enthusiasts and parties with vested interests. As research on makers, makerspaces and making is only now emerging, our understanding of everyday practices in makerspaces is also fragmented and largely reliant on groups' and individuals' own narratives. Rhetoric such as Rifkin's (and numerous other authors') may guide action as ideology and manifesto, but only direct observation of these activities and groups can reveal if makers' actions truly reflect these "beliefs" and "commitments" – or otherwise.

Identifying when and how makers enact ideology, and when not, can help articulate opportunities for more responsible practices in makerspaces. As Fab Labs are experimental spaces for new digital manufacturing capabilities and activities, and makers the actors practicing a possible future already now, there is much that can be learned about the potential coming impacts of ever-increasing digitalization in society and more citizen involvement in production. Fab Labs and makerspaces are especially spaces where new practices around open design and open innovation meet new uses of materials (and new materials) and energy-intensive production methods: where the espoused equipotentiality (Bauwens, 2005) of citizens globally for creative making and invention may or may not meet equitable global access to and use of energy and natural resources. There is clear potential for participants in the maker movement, such as Fab Lab users and organizers, to bypass the negative ecological impacts of mass production and consumption in their collaborative endeavours, but it is not self-evident that the actors even acknowledge or actively pursue this potential in their quest to change the present: change production, education and even the economy (Walter-Herrmann and Büching, 2013b). It can therefore be put forward that the sustainability analysis of these practices is best done sooner than later.

Among the citizen communities experimenting with digital fabrication, Fab Labs are a distinct entity and provide a distinguishable identity with which actors readily and eagerly associate. As will be explained further in the next chapter, the Fab Lab network is the most organized of maker communities: having clear communication facilities and channels networking the Labs; an abstract but widely promoted protocol for action; platforms for individual mobility, training and support across Labs; and regularly scheduled meetings for face-to-face interaction. Fab Labs therefore provide an excellent opportunity for examining peers making things together: organic enough that Labs differ widely from each other, while structured enough to enable observations of what commitments appear to maintain over time and across distance. Most importantly, such observations lend themselves to a better understanding of these novel spaces than mere identification of environmental issues in digital fabrication alone. The opportunities and hindrances to adoption of sustainability-oriented values and actions by these communities can be identified and understood as rooted in the community's local and geographic conditions, chronology and history, and interaction among actors: a more profound understanding involving time and change than can be delivered by quantitative evaluations (such as Life Cycle Assessments). This methodological advantage has also recently been acknowledged by other researchers, such as Hielscher and Smith (2014).

Given this background and the challenges outlined above, and highlighting the potential of Fab Labs to contribute to new production and consumption patterns in future, the key question is how (or if) these actors can co-create a more sustainable (i.e. environmentally, socially and economically sustainable) paradigm through collaborative, explorative activities based in Fab Labs today. In this doctoral research, this question is mainly examined through the lens of what actors actually do to both establish and use the Lab to fulfil their objectives: to articulate what current activities in Fab Labs tell us about the barriers and drivers to recognizing and prioritizing sustainability issues.

The research questions for the dissertation are as follows.

How do actors in the social world of a Fab Lab address environmental sustainability, in their future-oriented vision and strategy work and in their everyday operations? What are the environmental (often socio-environmental) issues in the maker movement and distributed production, and how are they discussed and tackled in Fab Labs?

The research methodology draws from approaches in Science and Technology Studies (STS), particularly Symbolic Interactionism and the social shaping of technology perspectives, and is informed by Design Research and the field of Design-for-Sustainability. Ontologically the research therefore takes a constructivist, interpretivist position. The methodology, methods and the researcher's standpoint are discussed in chapter 3.

In geographic scope, the research has focused mainly on the global North, particularly northern European Fab Labs. In scale, the dissertation particularly examines the 'middle range' of material peer production that is currently little studied: the actions and interactions of active practitioners and Lab organizers and the relationship between what they espouse and what they do. At this scale, as individuals form communities and social worlds, structural concerns such as existing institutional conditions meet actor- and material-related aspects, such as developing and learning new practices with technologies. As a unit (or units) of observation, this research target falls between the micro-level focus of individual Lab users' making actions (what they make, what motivates them, the role of 'creativity' and so on), a focus that receives more research attention, and higher-level observations of larger ecosystems (Fab Labs as innovation platforms, as alternative educational and socio-cultural spaces for neighbourhoods and municipalities, and so on). This larger body of research will be discussed further in chapter 2, and the scope of the research topic is discussed in more detail in section 2.2 and illustrated in Figure 4.

The audience that may benefit from the dissertation findings thus comprises researchers and practitioners from the fields of design and sustainable design, peer production, digital fabrication, user innovation, Sustainable Production and Consumption (SCP), futures studies and Science and Technology Studies. Also importantly, the findings and implications should help guide actors in Fab Labs to reflect on their future options and directions.

The next chapter will discuss the context and background of the dissertation topic and chapter 3 the theoretical positioning and methodology. Chapter 4 presents the summary of the research papers. Chapter 5 will synthesize and articulate the key findings and chapter 6 present their implications and final conclusions, followed by the original papers.

The first 'Hello world' test run of a new CNC milling machine in Aalto Fablab, Helsinki, Finland, in March 2014. Source: author.

2

DISTRIBUTED, OPEN SOURCE, MATERIAL PEER PRODUCTION

This chapter will describe the context within which the research for this dissertation was conducted and the terminology used in the various relevant research and practice arenas. How 'sustainability' enters into this discussion and how it can be examined, especially when observing non-hierarchical groups involved in collaborative, novel activities using novel technologies, is an important issue. This sets the stage for the methodological discussion in chapter 3: how the research was carried out in practical terms.

2.1 FAB LABS

Community workshops for digital fabrication are known as makerspaces. They come in a great variety of forms and funding models, from spaces in museums and libraries, to membership-based non-profit organizational spaces, to commercial services (Troxler, 2011). Fab Labs are an international network of makerspaces associated with Massachusetts Institute of Technology's Center for Bits and Atoms (CBA). While mainly self-organizing, the Labs share a common identity in the Fab Lab network (Figure 1) and meet regularly in regional and global meetings (the annual meeting of all Labs is known as FABx). Labs may also collaborate virtually and physically on common projects aimed at fostering the wellbeing of a particular community.[2]

2 for example, the Low Cost Prosthesis project (www.lowcostprosthesis.org) (accessed 23 April 2015)

FIGURE 1: The Fab Lab logo. Source: Center for Bits and Atoms, MIT.

FIGURE 2: The Fab Charter, in Fablab Amsterdam. Source: author.

Labs also encourage their users to collaborate and share designs, practices fostered by the acquisition of similar equipment.[3] They voice a commitment to the Fab Charter,[4] which all Labs are encouraged to display (Figures 2 and 3).

The loose, organic, non-franchise structure of the network owes to its origins: MIT Professor Neil Gershenfeld launched several Labs as an outreach project with funding from the National Science Foundation about fourteen years ago with no intention of forming a network (Gershenfeld, 2005; 2012). From the outset, the intention was to encourage hands-on

3 see www.fablabs.io/machines (accessed 23 April 2015)

4 www.fabfoundation.org/fab-labs/the-fab-charter/ (accessed 25 March 2015)

The Fab Charter

What is a fab lab?

Fab labs are a global network of local labs, enabling invention by providing access to tools for digital fabrication

What's in a fab lab?

Fab labs share an evolving inventory of core capabilities to make (almost) anything, allowing people and projects to be shared

What does the fab lab network provide?

Operational, educational, technical, financial, and logistical assistance beyond what's available within one lab

Who can use a fab lab?

Fab labs are available as a community resource, offering open access for individuals as well as scheduled access for programs

What are your responsibilities?

safety: not hurting people or machines
operations: assisting with cleaning, maintaining, and improving the lab
knowledge: contributing to documentation and instruction

Who owns fab lab inventions?

Designs and processes developed in fab labs can be protected and sold however an inventor chooses, but should remain available for individuals to use and learn from

How can businesses use a fab lab?

Commercial activities can be prototyped and incubated in a fab lab, but they must not conflict with other uses, they should grow beyond rather than within the lab, and they are expected to benefit the inventors, labs, and networks that contribute to their success

draft: October 20, 2012

FIGURE 3: The Fab Charter. Source: Center for Bits and Atoms, MIT.

activity and invention by bringing 'science and technology' to peripheral and marginalized communities (Gershenfeld, 2005). Since then (2002-2004), demand for local Labs has spread rapidly, initiated by various groups, from independent entrepreneurs to universities, and with varying amount of dialogue with MIT. There are now more than five hundred Labs around the world; the number doubles roughly every 18 months.[5]

Fab Labs are differentiated from other digital fabrication access spaces such as hackerspaces (Maxigas, 2012) and makerspaces (Troxler, 2011)

5 www.fablabs.io/labs (accessed 15 January 2016) by committing to open access to the general public and by more explicit dialogue and interaction among Labs, where Labs are expected to contribute to development of the network. This interaction is fostered when individuals meet each other when attending the global meeting FABx, the regional meetings (such as those of the Fab Asia Network, the Benelux Labs and Fab Lat, the regional association of Latin American Labs), and the Fab Academy. The Fab Academy is a distributed teaching programme for digital fabrication coordinated by MIT and conducted by assigned Labs as 'nodes' (Gershenfeld, 2012; Ghalim, 2013).[6] Fee-paying participants do weekly exercises involving all the equipment in the Lab to learn how digital designs ("bits") translate into material results ("atoms") and vice versa. Interaction among a highly diverse participant group in Fab Academy (virtually and in the Lab) as well as during the Labs' open access days also contributes to consolidating the peer learning aim and is espoused as key to innovation and creative problem solving. In practice, diversity in Fab Labs often intimates disciplinary, educational and (at times) age diversity rather than income and social status, unless the Lab specifically targets and/or is located in a marginalized, low-income community (Corbett, 2012; Maldini, 2013; Seravalli, 2014b; Hielscher et al., 2015). Gender diversity is also a concern of some researchers of makerspaces and hackerspaces (Carstensen, 2013; Toupin, 2014; Fox et al., 2015).

There have been several, but not many, attempts to map the Fab Lab network. Troxler (2010, 7) reports on a survey of ten Labs (the network at that time consisting of only 45 Labs), six of which were hosted at schools or research or innovation centres (see also Troxler and Wolf, 2010). By 2014, Fab Labs numbered in the hundreds.[7] Troxler (2014) noted the differentiation between hosted Labs (those hosted by schools, universities, innovation centres, regional development organizations and the like) and "grassroots" Labs initiated by individuals and groups, often with radically smaller budgets and reliant on subsidies, sponsors and/or membership fees. While Labs in the United States and those closest to the Center for Bits and Atoms and the Fab Foundation tended to follow the hosted model, many Labs in Europe were adopting their own models, finding their own funding and forming their own non-hierarchical associations (Troxler, 2014). Troxler estimated that in 2014 more than 50% of Labs in France and Italy were "grassroots" while the majority of Labs in e.g. Germany and the United Kingdom were "hosted" Labs (Troxler, 2014).[8]

In a typology developed by Eychenne (2012a), Labs surveyed were seen as supported by a school or university; as targeting entrepreneurs and small business support; or as targeting the general public ("pro-ams").

6 http://fabacademy.org/diploma/ (accessed 11 August 2015). The Fab Academy is largely built on experiences derived from Gershenfeld's popular MIT rapid prototyping course called How to Make (Almost) Anything (Gershenfeld, 2012).

7 By my own count, there were 300 Labs globally in mid-2014 (based on Labs listed in <http://wiki.fablab.is/wiki/Portal:Labs> on 25 June 2014).

8 A recent survey in Italy noted a lack of makerspaces, including Fab Labs, in (specifically) design schools and universities (Menichinelli et al., 2015). By my own count, only three Fab Labs are currently clearly hosted by an Italian school, university or college and the remainder constituting a mix of individual or group-founded Labs, municipality- or regional-authority hosted Labs and others (based on reviewing 57 Italian Lab websites as listed in <www.fablabs.io/labs> in January 2016). This is to be compared to the American list of currently active Labs, 63% of which are clearly hosted by universities, colleges or schools (primary, secondary or vocational) (an accounting based on reviewing 90 American Lab websites as listed in <www.fablabs.io/labs> in January 2016).

In all cases there was the expectation that the Labs are also open to the general public (Eychenne, 2012a). The last of these types may be hosted and/or supported by municipal or regional authorities or local media, art and cultural associations (as in the case of the Waag Society hosting Fab Lab Amsterdam) (Eychenne, 2012a). Both the second and the third type in this typology can thus comprise "hosted" Labs, but some may equally be considered "grassroots" Labs if they are seen as independent, founded by private individuals or groups, and thereby seek revenue through grants, membership fees or selling services.

An alternative typology was developed by Capdevila (2013) in a working paper that examined Fab Labs, co-working spaces, makerspaces and hackerspaces, and Living Labs. The results differentiated projects as mainly led by institutions; projects mainly led by users; "for profit" projects or those focusing on local economic development; and "non profit" projects or those focusing on social issues (Capdevila, 2013). Such a typology has potential to capture the intents of Fab Lab founders and organizers, the aims of their Labs and the target users. However all such surveys and studies attempting to map the Fab Lab landscape face the problem of tracking their rapid proliferation, as well as the challenge of chronology: how Labs change as their situations change. Nevertheless, for Troxler (2014, 2), a "forking" in Fab Lab development from hosted Labs to grassroots alternatives is a significant development, which causes concern as to whose narratives are ultimately taken up: that of conventional manufacturing and business development, or that of communities developing diverse, "decentralized or poly-centric and peer oriented" practices.

As for what happens inside Fab Labs, to my knowledge, there are no (or few) ethnographic studies on Fab Labs examining activities and actors similar to those on hackerspaces (Tanenbaum et al., 2013; Toombs et al., 2014; Toombs et al., 2015; Sun et al., 2015), except a Master's thesis, a research report and a follow-up paper focusing on Fab Lab Amsterdam (Ghalim, 2013; Maldini, 2013; 2014). The existence and nature of the espoused 'diversity' is thus largely anecdotal as yet and/or based on dispersed surveys covering only some Labs, as described above. Research on Fab Labs is clearly dominated by a focus on education and working with pupils or students (Millner and Daily, 2008; Blikstein, 2013; Sheridan et al., 2014; Dreessen et al., 2014). Another commonly seen topic is innovation and entrepreneurship (Gjengedal, 2006; Troxler and Wolf, 2010; Beyers et al., 2012; Dickel et al., 2014), and thirdly are reports of technical experiments and inventions that are usually of general HCI, Human Computer Interaction, interest (not necessarily specific to the Fab Lab community) (McGrath et al., 2012;

Mellis and Buechley, 2012). The ethnographic (and similar) studies of users in makerspaces and hackerspaces, what they do, what they prioritize, how they organize and so on, can be equally relevant and comparable to Fab Labs, their actors and activities. Nevertheless Fab-Lab-specific knowledge is valuable, given the strong identity of the Fab Lab network, its evolving, emergent structure and governance models, and the regular interactions between and among Labs.

However, the question remains: why do Fab Labs exist? Gershenfeld expresses several points of interest in having these distributed spaces for exploration, even if the umbrella mission for all activities described below is "to put control of the creation of technology back in the hands of its users" (Gershenfeld, 2005, 8). First (and likely his most personal interest), there is a (long-term) future envisioned of programmable and self-assembling, disassembling and re-assemble-able materials (Gershenfeld, 2005, 10, 241-244; Cheung and Gershenfeld, 2014). Secondly, he describes a (medium-term) future of Fab Labs that can reproduce their own machines and therefore themselves (Gershenfeld, 2005, 12), promoting the distribution of production, a topic that will much inform the organization of Fab12 in Shenzhen, China, in 2016.[9] Thirdly, and most well known, from the outset of the National Science Foundation grant, Fab Labs were established for educational outreach and, "instead of bringing information technology (IT) to the masses, fab labs show that it's possible to bring the tools for IT development, in order to develop and produce local technological solutions to local problems" (Gershenfeld, 2005, 13). Fab Labs were therefore explicitly established to address the digital divide between "developed" and "developing" countries (or privileged and underprivileged regions) in terms of fabrication tools (Gershenfeld, 2005, 13, 249-251). This mission is still largely relayed in media reports and Fab Foundation communications (Mandavilli, 2006; Lassiter, 2013) and may provide the grounds for such an emphasis in Labs on integration with formal education, no matter the region.

9 see http://cba.mit.edu/news/14_12.html (accessed 17 August 2015)

It can be argued that in the global South, in regions where access to resources (natural resources, technologies, tools, skills, education and the like) for the larger population is more limited, and regions are more vulnerable to the externalities of mass production such as natural resource exploitation, labour exploitation and pollution, Fab Labs have a clear role. Democratizing the means of invention and production, enhancing people's ability to meet their own local needs, would appear to have clear socio-economic *and* environmental, ecological benefits in these contexts. In the global North, however, where people are more highly educated, they have greater access to capital, and technologies are widespread even if not widely understood, what is the perceived need of a Fab Lab and fabrication tools? Two questions appear worth pursuing.

The first is how Fab Labs in the global North define their missions and visions and how they actually act: how aligned they become to any of Gershenfeld's and the CBA's espoused interests, given the truly self-directed, self-selecting and self-organizing nature of the network. The second question, and the more delicate to answer, is the potential of Fab Labs in the North to contribute to greater socio-environmental sustainability than our current economic system delivers. What role does environmental sustainability play in each of the agendas described above, and how do individual Labs subscribe to any of them? This is regarded particularly relevant as, despite the extent of the rhetoric espousing Fab Labs as bringing technology to the marginalized, 75% of Fab Labs are in "developed" countries (Sperling et al., 2015, 407). Some Labs have a clear purpose and explicit understanding of their role in exploring environmental sustainability opportunities, as described in Smith et al. (2015) and paper 4. Before moving to the environmental discussion, however, the following section provides more contextual information on the social arena and research field of material peer production.

2.2 THE MAKER MOVEMENT AND PEER PRODUCTION

Fab Lab users and users of personal fabrication technologies globally form a loosely categorized community called the maker movement, a term likely popularized by the American Make Magazine who also organizes the Maker Faire franchise.[10] 'Makers' share their creations and inventions on websites such as 'Thingiverse', they show their work in Maker Faires and similar fairs, and, even without having to access the machines themselves, they can order bespoke products from online services such as Shapeways.[11] 'Doing' digital fabrication is also known as 'making' and 'fabbing'.

10 http://makermedia.com (accessed 11 August 2015)

11 www.shapeways.com (accessed 16 October 2015)

Today's maker movement thus embraces traditional handicraft and "craft consumption" (Campbell, 2005), as well as various DIY (do-it-yourself) activities (Atkinson, 2006; Shove et al., 2007), but it is marked by an interest in technology and digital fabrication: "both small *and* global. Both artisanal and innovative. Both high-tech and low-cost. Starting small but getting big" (Anderson, 2012, 16; emphasis in original). Gershenfeld (2005) himself prefers the term "personal fabrication", and Bauwens et al. (2012) have termed making "personal manufacturing". Building on its congruencies with similar peer-to-peer phenomena in open source software and digital production such as Wikipedia, which Benkler (2006) termed "commons-based peer production", Troxler (2013) offered the term "commons-based peer production of tangible goods" and Raasch et al. (2009) "open design". What lessons can be learned from open source, commons-based peer production when it enters the realm of tangible products is an emerging topic of research (Malinen et al., 2011; Powell, 2012; Kostakis and Papachristou, 2014).

Commons-based peer production is a "new modality of organic production: radically decentralized, collaborative, and non-proprietary; 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" (Benkler, 2006, 60). Proponents of peer-to-peer collaborative and cooperative models emphasize the benefits of the use value generated over profit and exchange value; the effectiveness of a network where testing and reiterating can be done by many more, diverse individuals; and the ethical, equitable benefits of a commons based on culture, creativity and knowledge (Bauwens, 2005; 2009; Benkler and Nissenbaum, 2006; Leadbeater, 2008; Tapscott and Williams, 2008). In such models, the openness by which knowledge and assets are shared (and when they are not) can determine the success of the system, hence the growing interest in understanding how such communities of practice (Wenger, 1998) self organize, self govern and distribute tasks, responsibilities and risks.

This dissertation will therefore use the terms personal fabrication, digital fabrication and material peer production interchangeably to refer to these making activities. Personal fabrication tends to emphasize DIY agency, digital fabrication the use of digital tools, material peer production emphasizes the collective peer-to-peer nature of the production mode, while distributed production denotes fabrication activities (also commercial/industrial) differentiated from conventional mass production (Figure 4).

Figure 4 illustrates the research scope of this dissertation. The commonly used term 'Web 2.0' refers to internet activities that involve more peer-to-peer engagement and sharing and adaptation of others' content than the first incarnation of the World Wide Web did: comprised as it was of simple viewable websites (even if citizen created) with little interaction. The term Factory 2.0 accordingly refers to 'the next version' of conventional mass production factories, which are distributed and enable personalized production with the help of digital manufacturing equipment.[12] Digital fabrication capacity thus differentiates both Factory 2.0 and DIY 2.0 from their analogue counterparts: DIY 2.0 embracing handicraft, but marked by the ability to use CNC equipment and build electronics, as well as the collaboration on and sharing of digital designs and plans. The diagram intends to highlight that the term 'prosumption' is often used in research

12 The 2.0 designation refers to the convention in software development where new application versions are accorded higher titles: 1.0, 2.0, and so on. Given the popularity of this trope applied in many appropriate and inappropriate contexts, it is surprising the term Factory 2.0 has not found wider usage as yet (see for example Fox, 2009).

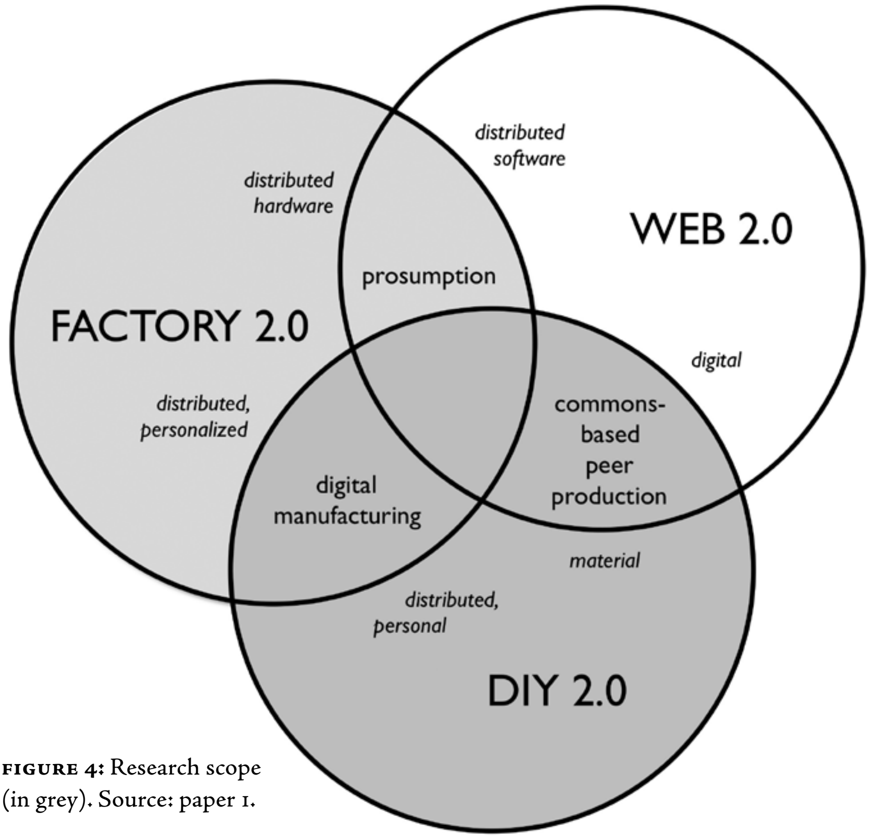


FIGURE 4: Research scope (in grey). Source: paper 1.

on Web 2.0 practices as well as new distributed manufacturing activities (such as mass customization; Pine, 1993), as indicated in paper 1. Commons-based peer production began with a focus on digital artefacts, but the term is increasingly also used for material peer production. Solely digital peer production artefacts such as software or Wikipedia are out of the scope of this dissertation, which focuses on spaces where material artefacts are produced by lay citizens in a regime of peer-to-peer interaction.

2.3 DISCOURSES IN PEER PRODUCTION

It is important to note the range of references peppered in the previous section, as the benefits of peer production are positioned differently by different researchers and writers, from Marxist to liberal economics to STS perspectives. Writing about open hardware, Powell (2012, 697-698) emphasized how material peer production is represented by a variety of different relationships to the market: outside it, "agnostic" to it, creating new markets, to disrupting existing markets. This variety makes for an uneasy mix of interests and strange bedfellows, and it manifests in controversy: increasing critique from within and outside the maker movement. Critics write that the movement's virtuous goal of promoting local socio-economic opportunities for maker inventors and micro-entrepreneurs is being overshadowed by the promise of success of another kind, measured in economic profit and ensuring this profit by proprietary, protectionist means (as large corporations tend to do): precisely the elements makerspaces (and especially Fab Labs) were seen to set up to counter (Morozov, 2014; Draitser, 2015; Fonseca, 2015). For other critics, the movement's claim that making is a meaningful, self-empowering, democratic act for its makers and a better, freer alternative to a consumerist worldview is belied by observations that in practice, making is merely another form of unsustainable commodification (Arieff, 2014) and makers only appear to "play with tools and make personalized schlock" (Sadowski and Manson, 2014); "exclusive knick-knacks for the anomic plutocracy" (Poole, 2012); or "crapjects" (Smith, 2012). As highlighted in paper 4, the call for critical discussion is also coming from inside the Fab Lab network via social media (such as a LinkedIn interest group) and editorial journal articles (Nascimento, 2014; Maxigas and Troxler, 2014; Troxler, 2014).

These contending views on peer production are also reflected in the historical antecedents to which the writers above refer. Almost without exception, every proponent of the maker movement will invoke its roots in and similarities to the early development of the personal computer (Anderson, 2012; Gershenfeld, 2005) and especially the Homebrew Computer Club (Wozniak, 1984), out of which grew the Apple computer in the 1970s (Anderson, 2012). Rifkin (2014) further proffers Stallman's Free Software movement of the 1980s (Stallman, 1983) as having a role. He especially points to the influence of Stewart Brand, who managed to bridge these early hacker communities in California with the possibly otherwise disparate communities associated with the Appropriate Technology and back-to-the-land movements of the 1970s, with the help of Brand's Whole Earth Catalog and The Whole Earth 'Lectronic Link (WELL): an early and seminal "virtual community" (Rheingold, 1993) (Rifkin, 2014). For Rifkin (2014, n.p.), these developments serve as the backdrop to the current Third Industrial Revolution, in which Fab Labs have a crucial, explicit role: "Fab Labs are the new high-tech arsenals where DIY hackers are arming themselves with the tools to eclipse the existing economic order".

For technology critic Morozov, these developments are not symbols of a utopian coming-together-of-minds, but indications of our limited possibilities in a digital future. In The Baffler, Morozov (2013) related the story of the ideological split in the 1990s between Stallman's Free Software movement and O'Reilly's open source software movement, where O'Reilly's individualistic, libertarian, "Randian" visions of software that embraced the business community came to predominate over Stallman's more political, communal, overtly ethical vision centred on ordinary users and their rights to understand and control software. (Tellingly, the O'Reilly here is the O'Reilly of O'Reilly Media, which owns Maker Media – of Make Magazine and Maker Faire fame.) For sociologist Flichy (2007), similar forces have been at play over the fate of the internet, as a platform for communities and free expression or business and free markets, where regulation is seen as necessary to protect cyber-citizens from big business, on the one hand, or the tyranny of the state, on the other.[13]

Flichy (2007, 165-166) nevertheless highlights that the common understanding (in some circles) that the internet has been co-opted by capitalism "oversimplifies the issue" and "the commercialization of the Internet is a complex process, in no way identical to the commercialization of the preceding media." Sociologist Turner (2006) has also painted a more nuanced and detailed picture of Brand's brand of cybernetics than Rifkin attempted, tracing Brand's (and the WELL's) influence up to Wired magazine[14] and even to players in large corporations and American politicians on the far right: odd bedfellows indeed with back-to-the-land hippies. Turner's depiction (2006, 4, 8) is thus less a story of co-option – the revolutionary counterculture being swallowed by the powers of the military-industrial complex, corporate capitalism and consumerism – than the formation of a communal-minded yet libertarian and entrepreneurial ethos that all these seemingly distinct communities could champion.

Though critique may come easy, it is similarly tempting to oversimplify material peer production as being co-opted by a malevolent entity or promoting a particular good or a particular bad, whether corporate capitalism, consumerism or neoliberalism.[15] As Powell points out (2012, 698), "This complexity [of open hardware's relationship to markets] highlights the contingent nature of efforts to democratize further the processes of technology development" – inside and outside the market. In turn, this contingency calls for empirical study of what actually happens in these communities in order to inform public discussion, and foster literacy, on these sociotechnical arrangements.

In this dissertation, these discourses on peer production and the digital society thereby form as much a part of the empirics as the ethnographic fieldwork: they are described here in chapter 2 as background, but they

13 The comparison between Bre Pettis's Makerbot, which became a closed source, proprietary 3D printer owned by Stratasys, and Adrian Bowyer's RepRap, which remains an open source, fluid and flexible design (that gave birth to the Makerbot), is often seen by observers as a similar ideological split (see Brown, 2012). Incidentally, the Makerbot was born in a hackerspace and the RepRap in a university.

14 a magazine for which Anderson, writer and influential maker myth-creator (2012), later came to be editor-in-chief

15 or, as Thrift (2011) put it so splendidly, the "security-entertainment complex" appear as key elements of the analysis also in paper 4 and the discussion in chapter 5. As Clarke (2005, 30, emphasis in original) writes, "The important so-called contextual elements are actually *inside the situation itself*. They are *constitutive* of it". The presentations of ideology, critique and counter-critique as described above influence the Fab Lab social world and what actors decide to do: "It is this ideology that is used to legitimize the new technique, to attract and integrate new users, to provide a framework for use of the innovation. It also affords a set of justifications that enable designers and users alike to explain their engagement in the digital world" (Flichy, 2007, 208). Historical presentations and seminal figures (such as Stewart Brand or, equally, William Morris) are also used by communities to construct and present their collective vision, or *imaginaire*, in Flichy's terms (2007, 109). It is up to the researcher to trace these influences, as seen in Bruce Sterling's apparent impact on Fab Lab managers in paper 4. Researchers are in fact implicated in the drama, putting forward their own scenario exercises as (utopian) alternatives (Easton, 2009; Birtchnell and Urry, 2013a; Potstada and Zybura, 2014; Tanenbaum and Tanenbaum, 2015).

Hyysalo (2006; 2010) thus highlights the importance of understanding the *imaginaire* or "practice-bound imaginary" (Hyysalo, 2006) from which a particular group draws: "the relatively integrated sets of visions, concepts, objects, and relations that practitioners regarded as desirable, relevant, potentially realizable, and as having cognitive and motivational power for organizing *their practice*" (Hyysalo, 2010, 76; my emphasis). In particular, paying attention to the various contending views on peer production means attention to the "interanimation, layeredness, and conflicts" between and among different imaginaries, in order to better understand how these groups and their practices change (Hyysalo, 2010, 77). For example, technologies in a Fab Lab may be perceived, construed and contested as toys for non-professional hobbyists, low-cost inclusive tools or open and adaptable entities for highly skilled technicians, depending on with which practices and *imaginaires* they become associated.

For Pfaffenberger (1992), as elucidated in paper 4, these contesting positions constitute a *technological drama*, where digital fabrication technologies have been appropriated from production hegemony and reconstituted as counterartefacts in countercontexts: the tools of revolution in Fab Labs. The process of antisignification in this drama is the 'casting' of attribute characters: the roles sociotechnical materials and processes must play as, for instance, 'distributed' and 'decentralized', 'democratic', 'empowering', 'local' and 'open', if they are to appear on the Fab Lab stage. The setting of alternative agendas can also be understood in terms of "root paradigms", which are "cultural models for behavior, maps for interpreting social relations in terms of cultural meanings, that are at once deeply resonant and logically inconsistent" (Pfaffenberger, 1992, 298, referring to Turner, 1974). The dominant paradigm has its root paradigms; the challenging social worlds such as Fab Labs redefine them. Root paradigms exist as worldviews but not guides for actions: they and their logical inconsistencies rather serve to "generate a profusion of action strategies, all of which can be presented as legitimate" (Pfaffenberger, 1992, 298).

These inconsistencies and ambiguities are a key part of the controversy: whether a sociotechnical assemblage such as an open source 3D printer, its filaments mass manufactured in China and shipped to Finland, a designer maker, an open source design, a fabrication space in a university, a helping peer, a particular fabbed object as outcome and a blob of plastic as waste, is decentralized and decentralizing, empowered and empowering, democratic and democratizing, local and localizing, and so on – is less than self evident. As communities shape technologies, and technologies shape communities (Heiskanen et al., 2010), ideology is co-constructed yet again while individuals run up against – and exist within – conventional social institutions and everyday, mundane routines.

The result for the maker movement and the Fab Lab network in its current form is to be seen as "ad hoc ashrams", a rather delightful phrase delivered by commentator Eric Hunting in the Open Manufacturing Google group in 2009. Hunting wondered why take-up of open manufacturing and the maker movement was proceeding so slowly:

> People are learning by making, but they never seem to get the whole picture of what they potentially could make because they aren't getting the complete picture of what the tools are and what they're capable of.... Remember the early days of the personal computer? You had these fairs, users [sic] groups, and computer stores like Computer Shack basically acting like ad hoc ashrams of the new technology because there were no other definitive sources of knowledge. This is exactly what Maker fairs, Fab Labs, and forums like this one are doing. (Hunting, 2009; as cited in Carson, 2010, 249)

To clarify, an ashram is a dedicated and separate place (building or space, akin to a monastery) for Hindu spiritual practice. Seeing a Fab Lab as an "ad hoc ashram" identifies both its self-perceived role as purveyor of enabling, empowering production capabilities, a separate and distinct place in which to learn and grow, as well as its early stage of development: ad hoc, not yet consolidated or routinized and not yet widely understood as infrastructure for new maker activities. Indeed, Computer Shack and similar actors (from internet cafés to computer repair entrepreneurs) have been identified in innovation scholarship as innovation intermediaries, who configure technologies, facilitate new users and uses, and broker connections between different actors (Stewart and Hyysalo, 2008). Seen as user-side intermediary actors, then, Fab Labs offer "spaces and opportunities for appropriation and generation of *emerging* technical or cultural products by others who might be described as developers and users" (Stewart and Hyysalo, 2008, 296-297; emphasis in original).

Such 'ashrams' (or ecosystems of various intermediary ashrams) can configure users, contexts, the symbolic meaning of making and even the technologies to a certain extent, but they cannot control or define use (Hyysalo, 2010, 18). Their position in the sociotechnical middle layer, as novel actors mediating between production chains and new prosumption activities, requires strong and convincing 'spiritual gods' and guides, in the form of myths, ideologies and *imaginaires* that do their best to leave the other, more stable, social worlds and dominant root paradigms (as well as competing intermediaries) in the shadows. As Fred Turner (2006) and Flichy (2007) highlighted, however, in the case of the WELL virtual community and the development of the internet respectively, this can have very real consequences. The sheer virtuality of Brand's cybernetic vision and the internet can push 'real life' aside; the implications for tangible earth and body are then easily ignored. According to Turner,

> The rhetoric of peer-to-peer informationalism, ... much like the rhetoric of consciousness out of which it grew, actively obscures the material and technical infrastructures on which both the Internet and the lives of the digital generation depend. Behind the fantasy of unimpeded information flow lies the reality of millions of plastic keyboards, silicon wafers, glass-faced monitors, and endless miles of cable. All of these technologies depend on manual laborers, first to build them and later to tear them apart. This work remains extraordinarily dangerous, first to those who handle the toxic chemicals required in manufacture and later to those who live on the land, drink the water, and breathe the air into which those chemicals eventually leak [footnote removed]. These tasks also continue to be the province of those who lack social and financial resources. (Turner, 2006, 260)

This suspension of other realities and their invisible implications apply equally to Fab Labs, as the conventional realities of home and work become suspended (paper 3) and implications of digital fabrication rarely seen or discussed, from supply chains to energy sources to unsafe working conditions (paper 4), even if clear consequences of a digitalizing society. Environmental issues and their practical implications will be introduced in the next section, especially in view of how they can be best researched and discussed.

2.4 ENVIRONMENTAL ISSUES, DISCOURSE AND FRAMINGS

As an entity encompassing a place, people and practices, Fab Labs court paradox and complexity regarding appropriate use of materials and energy. The research focus in this dissertation is therefore first and foremost on environmental sustainability, which does not intend to disconnect it from the intertwined social and economic sustainability questions. Rather, as much attention is already directed to the socio-economic dimensions of distributed production (or "prosumption": Toffler, 1980; Ritzer and Jurgenson, 2010), foregrounding environmental sustainability serves to amplify if or where the gaps exist between what is espoused and what is practiced. (This is also a methodological question that will be discussed further in chapter 3.)

Beyond the literature review of paper 1, which examined research on distributed production and environmental impacts, several recent studies carry practical implications for current Fab Lab practices. Somewhat surprisingly, some researchers appear to be targeting the small-scale personal fabrication audience, in contrast to the industrial additive manufacturing arenas largely present in the empirical studies summarized in paper 1. A life cycle assessment exercise, for example, explicitly made fabrication spaces its target audience: it was carried out so "prototypers and job shop owners can make an informed decision about which technology to purchase or use, and so the makers of 3D printers can understand their priorities for improving environmental impacts" (Faludi et al., 2015, 15). Faludi et al. (2015) concluded that prototyping with desktop 3D printers (rather than CNC milling machines) may be less environmental impactful than first thought, but this is dependent on high utilization of the printer. This conclusion appears rarely exploited by Fab Labs: by being shared, open, peer-learning spaces, they boost the potential for eco-efficient use of shared equipment. They may also remove health, safety and emission problems away from the home or office, given appropriate health, safety and waste management measures are adopted in the Lab. Stephens et al. (2013) examined ultrafine particle emissions from desktop 3D printers and recommended caution in use in inadequately ventilated spaces. (Ventilation, filters and careful procedures are more clearly observed with the use of laser cutters and milling machines in makerspaces than 3D printers.) This was also the conclusion in Short et al. (2015) (who examined more 3D printing technologies than Stephens et al., 2013, and not only in the context of personal, desktop machines); the authors expressed concern that environmental impacts (and health and safety issues) of many materials used in additive manufacturing remain unknown, including when they begin to degrade. These hazardous issues, connected to process waste, support materials, resins, finished products and so on, impact not only people in the fabrication space, but also people downstream in the waste cycle as well as natural ecosystems at final disposal. This issue will become even more prominent as other types of 3D printers are developed based on expiring patents. (Desktop 3D printers have up until recently been solely FDM, fused deposition modelling, printers; low-cost, desktop SLA, stereolithography, printers are now entering the market whose materials and processes are less certain to be benign.)

Hunt et al. (2015) identified the challenge of recycling the polymers used in personal 3D printers, and to that end developed a model for recycling codes that could be deployed in the United States as well as the design scripts that could print the codes into the products. The same research group (Michigan Tech Open Sustainability Technology) also examined the life cycle benefits of distributed recycling: a scenario where home users and prosumers would perform their own recycling processes from post-consumer goods for their own future 3D printing processes (Krieger et al., 2014). These studies are rather unusual in that they project for a scenario where small-scale, distributed, open manufacturing exists and then conduct studies to pre-empt the barriers to the environmental sustainability of such a system. A similar strategy can be seen in Kostakis et al. (2013), who explored the viability of a new social production mode oriented to sustainability, desktop manufacturing and commons-based peer production, via a case study of an open source wind turbine design.

Fox (2014) also discusses these barriers by examining the opportunities and limits "mobile production" (as opposed to "fixed production") and "Third Wave DIY" face in terms of production, innovation and entrepreneurship. Environmental benefits include less use of raw materials and energy when compared to fixed production, but Third Wave DIY requires access to industrial infrastructure: "reliable electricity supplies, plentiful water resources, and comprehensive transportation systems" as well as language and computer skills (Fox, 2014, 26). Moreover, Fox highlights the low revenues in this mode of production (and relatively high set-up and storage costs), which necessitate subsidies. These conditions help explain why – despite rhetoric – Fab Labs have less take-up in Africa, for instance, especially outside of universities, and how the circulation of Fab Labbers educated in Europe and North America have spurred the growth of Fab Labs and makerspaces in South America, as reported in Sperling et al.'s (2015) study. This is a fruitful area of future research: how these global influences and Labber migrations come together with how Fab Labs address local specificities and regional socio-environmental concerns (Sperling et al., 2015; see also Smith, 2014).

At the Factory 2.0 scale (Figure 4), Hermann et al. (2014) proposed a model of future factories that would better accord with all three dimensions of sustainability, environmental, social and economic. In their prescriptive model, Fab Labs have a role within the factory supporting prototyping and personal fabrication, employee learning and regional support. Basmer et al. (2015) presented a conception of Open Production involving distributed production via micro-factories, including peer production, that, for these authors, represents more opportunities for social sustainability than the present. These studies complement other lines of inquiry now emerging that discuss the role of Fab Lab in sustainable cities (Diez, 2012; 2014; Guallart, 2014; March and Ribera-Fumaz, 2014). This compelling arena of research will not be summarized here but will be pursued in future studies.

These recent studies therefore appear to be taking a new direction, acknowledging a future where manufacturing is distributed and small scale and peer production has a clear role. They may be placed in the constructs of 'bespoke fabrication' and 'mass fabrication', little addressed as yet, as depicted in Figure 5 below (which appeared as Figure 4 in paper 1). They may also represent small steps to a better understanding of the under-addressed areas of research in Figure 6 below (which appeared as Figure 1 in paper 2).

Nevertheless, particularly when considering the opportunities and threats of a new distributed production paradigm, as represented on the right side of Figure 6, significant challenges remain in deciding how to best study them. Part of the challenge lies in dealing with complexity and large system boundaries if one is comparing mass production to distributed production. A related challenge is the quantification of socio-environmental aspects that are less amenable to measurement, as Gebler et al. (2014) attempt to do. Hielscher and Smith (2014, 44) thus point out the limits to methods such as LCA (life cycle assessment) studies and argue that, "[g]enerating insights into the contending narratives influential in digital fabrication developments… might be a more fruitful line of inquiry. Studying the cultures of production and consumption cultivated in workshops and other

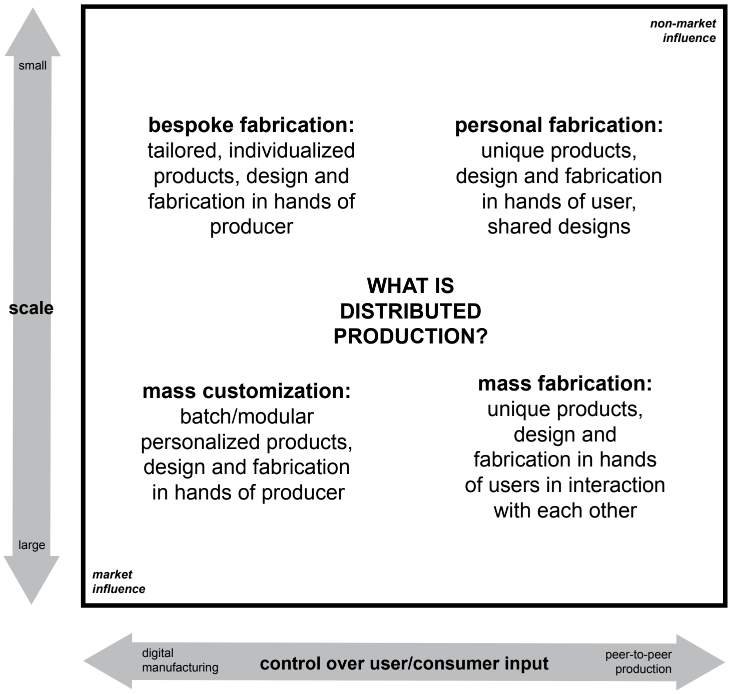


FIGURE 5: Conceptualization of distributed production. Source: paper 1 (adapted).

sites of take up seem to be key, and therefore how technologies are valued and used".

In recent literature (the small body of research that it is), there have been several ways adopted for the study of makers and maker communities and evaluation of their importance and implications. As introduced in section 2.2, the notion of the commons, as central to commons-based peer production (Benkler, 2006), is increasingly used (Troxler, 2013). In examining makerspaces in Mälmö, Sweden, Seravalli (2014a; 2014b) employed direct observations and active engagement in the communities to both articulate the dynamics of the communities and determine how design can best support such activities, analysis supported by employing a commons frame (Ostrom, 1990; Hess and Ostrom, 2007). There are different understandings of the "commons" that need to be articulated in such analyses. According to Seravalli (2014a), the original conception was that of natural resources as common-pool resources, whose use and access must be managed collectively (Ostrom, 1990; Hess and Ostrom, 2007; as discussed in Seravalli, 2014a, 60-61). Secondly arose concern with the "new commons", "open commons" and perceived "public domain" where knowledge, information, culture and innovation should reside (Lessig, 2002; Hess, 2008;

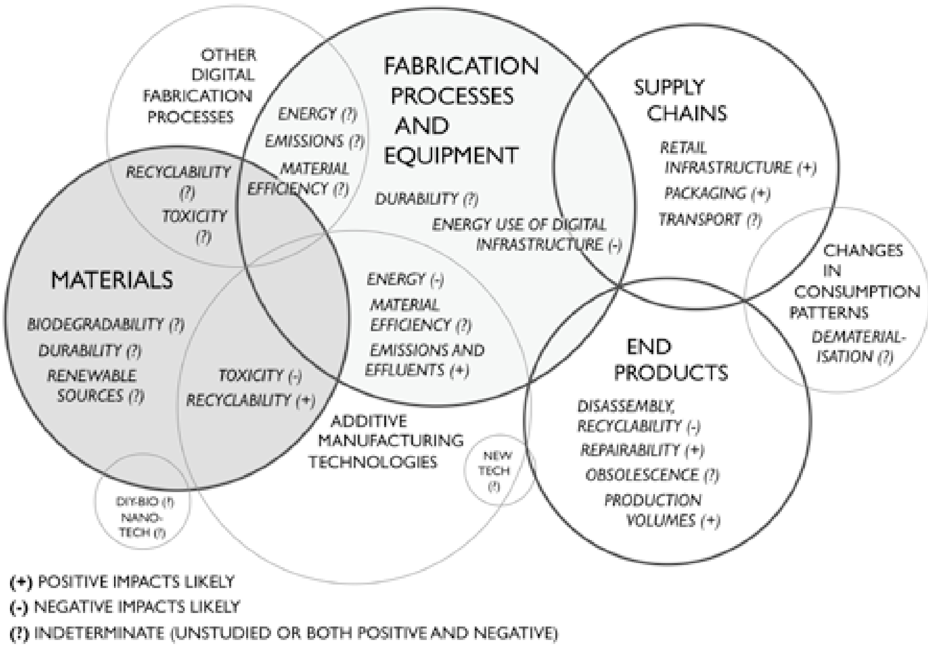


FIGURE 6: Overview of the environmental issues in distributed production and personal fabrication. The areas in grey have received the most research attention, as summarized in paper 1. Source: paper 2.

Benkler, 2013; as discussed in Seravalli, 2014a, 62-63). The third conception of the commons is that of a new social and economic system, a collective institution(s) that would manage both types of commons as an alternative to capitalism (Bollier and Helfrich, 2012; Seravalli, 2014a, 64-65). Given the recent popularity of commons framing in analysing maker communities, there appears some danger that, if attempted with any less of the sensitivity and sustained effort shown by Seravalli, it too adopts the characteristics of ideology: aggrandizing of strengths and oblivious to weaknesses, and/or dominated by concerns with the "new commons" and masking the seemingly more distal problems of the natural resource commons (as Flichy and Turner found, as discussed in the previous section).

The notion of "publics" has also been employed in the analysis of material peer production communities, such as Corbett (2012) examining Access Space in Sheffield according to Habermas's (1989) concept of public sphere and Fraser's (1992) counterpublics. Several researchers (and researcher-practitioners, particularly in the HCI arena), are turning to Dewey's ([1927] 2012) notion of "a public", a group of citizens who form specifically to address a problem previously seen as out of their control (DiSalvo, 2009; DiSalvo et al., 2014). The intent of this work is to focus attention on these problematic issues and how to enhance democratic processes in doing so; objects and materials (such as technologies) play a particular role in these studies. One line of enquiry particularly centres on critical discussion via making activities: generating critical understanding of technologies (for publics and scholars alike) by tangibly making them, either as designers alone (for, for example, exhibitions or provocative happenings) or with the publics in question (DiSalvo et al., 2014). Many have adopted Ratto's (2011) term of Critical Making for these endeavours, as discussed in paper 4 (Ratto et al., 2014; Ratto and Boler, 2014). While environmental sustainability may or may not come to the forefront of the problems regarded significant in these publics-oriented explorations (or in studies framed as commons-based analyses), Marres (2012) has examined the role of materials specifically with regard to environmental sustainability: how publics coalesce around environmental topics in everyday practices and how the materials or devices in question mediate participation.

An explicitly environmentally oriented framing of personal fabrication is that of Appropriate Technologies (Schumacher, 1973; UNEP, 1978, 44), as employed by, for instance, Turner (2010) and Pearce et al. (2010). As befitting the common definition of Appropriate Technology, both studies are centred on "development" and digital fabrication tools as empowering communities in the global South. There appears to be an opportunity to begin to define what and how digital fabrication tools are "appropriate" technologies in specific contexts in the global North, especially given the positioning of personal fabrication tools as low overhead and resource efficient (Carson, 2010) and that the phrase is employed in the Fab Lab community (Mandavilli, 2006; "Principal Voices: Neil Gershenfeld", 2008). Smith and colleagues' choice of term "grassroots innovation" (Smith et al., 2013; 2014; Hielscher et al., 2015) serves as a catch-all that can also include the material peer production communities in the global North. Recent focus on Fab Labs and makerspaces regards them as "community-based digital fabrication workshops" and "grassroots digital fabrication": as the (potential) setting for environmentally and socially conscious, appropriate technology development (Hielscher and Smith, 2014; Smith et al., 2015; Charter and Keiller, 2014).

Recent developments in Europe have seen other researchers and non-profit organizations attempting to explore and articulate Fab Labs' and makerspaces' potential role in a more socio-environmentally benign economic system, to exploit the immense pool of valued, specific knowledge and competence in Fab Labs on fabrication processes, electronics, components and materials. Current topics include remanufacturing and distributed manufacturing (the Future Makespaces project[16]) and closing material loops in a circular economy framework (The Ellen MacArthur Foundation;[17] the RSA's [The Royal Society for the Encouragement of the Arts] Great Recovery;[18] and the independent, self-organized Open Source Circular Economy Days[19]). These organizations' events in very recent years have seen enthusiastic Fab Lab participation and contribution.

This chapter has described Fab Labs and the current understanding of the maker movement. It has summarized relevant studies and trends in research on making and demonstrated how the environmental discourse has travelled both through the maker community and the research community studying material peer production.[20] Much research focuses on education and the social benefits of Fab Labs, and in parallel much discourse in Fab Labs touches on environmental issues only obliquely. This may be because environmental concerns appear too distant to be of concern in a small, "third-space" world of its own and/or Labs may feel underequipped to discuss environmental issues (as might researchers feel underequipped to study this fast-moving phenomenon). The current doctoral research puts forward that a better understanding of the activities and interactions in these forerunner fabrication spaces will help better identify both the socio-environmental issues of prominent concern and how to best tackle them. The research strategy for this dissertation was set accordingly, and the methodology will be described in the next chapter.

16 http://futuremakespaces.rca.ac.uk (accessed 21 August 2015)

17 www.ellenmacarthurfoundation.org (accessed 21 August 2015)

18 www.greatrecovery.org.uk (accessed 21 August 2015)

19 https://oscedays.org (accessed 21 August 2015)

20 This examination has obviously focused on English language studies and discourses, English predominating as the lingua franca in the US and northern Europe. Fab Labs are also discussed in other languages in the other regional networks, notably Spanish and Portuguese in the strong Latin American Fab Lab network, and in southern Europe, publications have appeared in Italian (Menichinelli and Ranellucci, 2015; Bianchini et al., 2015) and French (Eychenne, 2012b; Bosqué et al., 2014; Menichinelli et al., 2015). Discussion of these publications and discourses is out of scope of this dissertation.

Fablab Amsterdam, the Netherlands, December 2014. Source: author.

3

METHODOLOGY

The research conducted for this dissertation was carried out in a constructivist, interpretivist approach, emphasizing that technologies are socially shaped (Williams and Edge, 1996; Russell and Williams, 2002). Science and Technology Studies (STS) (Hackett et al., 2008) therefore provides the epistemic frame, while my background in Design-for-Sustainability has provided certain lenses for observation regarding design, design research and sustainable design (Charter and Tischner, 2001; Woodhouse and Patton, 2004; Tukker et al., 2008; Wahl and Baxter, 2008; Vezzoli et al., 2014).

3.1 SYMBOLIC INTERACTIONISM SENSITIZING FIELDWORK AND ANALYSIS

As articulated in paper 4, Symbolic Interactionism (Blumer, 1969; Reynolds and Herman-Kinney, 2003) was deemed an appropriate analysis frame for the ethnographic fieldwork, whereby the Fab Lab was studied as part of a social world (Strauss, 1978; Clarke and Star, 2008): "The particular power of the social worlds framework is that precisely because social worlds are 'universes of discourses' the framework explicitly goes beyond 'the usual sociological suspects' – conventional, highly bounded framings of collective actors such as organizations, institutions, and even social movements. These 'suspects' are displaced in the social worlds framework by more open, fluidly bounded, yet discourse-based forms of collective action" (Clarke and Star, 2008, 116-117).

Fab Labs seen as a "universe of discourses" (Strauss, 1978; Clarke, 2005, 55) thereby emphasize the rhetorical and ideological representations that are collectively shaped (Clarke and Star, 2008), alongside the interactivity that comes with a group sharing resources in order to accomplish goals (Clarke and Star, 2003). The "objects" in the Fab Lab social world are both materials and concepts (Blumer, 1969; Clarke and Star, 2008), supporting analysis of ideology and discourse *versus* practice: in other words, if Fab Lab actors are espousing environmentally oriented ideals, the enactment of these ideals should be visible in what the actors *do*, in this particular space and with the materials around them. This understanding helps avoid problematic concepts such as "attitude" in studying "behaviour-attitude gaps" (Kollmuss and Agyeman, 2002), a common approach in Sustainable Consumption and Production research as highlighted in paper 4, and a framing less suited to novel prosumption.[21]

The analysis thus allowed focus on the role of the materials (matter, tools and technologies). The materials are, after all, the channel or medium by which people become inspired and involved in a Fab Lab, participate, contribute, learn, interact with external stakeholders, seek monetary profit, initiate DIWO (do-it-with-others) projects, become disengaged, communicate vision, include some in interaction, while blocking others. They thus embody ideology and intent as much as convenience and convention. In this understanding, materials not only represent and mediate participation; they can be examined as constitutive of both agency and structure (Sandstrom and Fine, 2003; Clarke, 2005, 63). Such an observation and analytical lens can help consider the less discussed routines and routinization dynamics (Strauss, 1993), the way practices and sociotechnical ensembles can become *pre-configured*, especially in light of the role they play in sustainability awareness and operationalization. Symbolic Interactionism as an analysis framework was thus adopted as fitting the aims of the study: congruent with and conducive for studying the take-up of environmental concerns as well as how a Fab Lab is physically and ideologically built.

3.2 METHODS AND DATA COLLECTION

Paper 4 constitutes the main research focus for the dissertation. The data for paper 4 was gathered through ethnographic methods and semi-structured interviews in a longitudinal (more than three years') process. The subject of the study was the building of a new Fab Lab in a European university's art and design school, within a newly formed unit aimed at multidisciplinary, explorative research and teaching in the field of media and new media. The study began while the Lab was being physically built and continued as it opened, first to the university community and subsequently to the wider

21 'Practice' is thereby used as a term here to describe actions involving behaviours and interactions with actors and artefacts (both old or conventional and new), as found in maker communities. My intent is to distinguish the study of maker practices from understanding behaviour or analyses of pro-environmental behaviours, as seen in Sustainable Consumption and Production research (for example, DEFRA, 2008) and branches of sustainable design research (Lilley, 2009), on the one hand, while emphasizing that neither are practices-as-entities the sole unit of analysis here, as in some forms of practice theory (Reckwitz, 2002; Shove et al., 2012). From this perspective, people "doing things together" (Becker, 1986) in a Symbolic Interactionist understanding are not simply performing known, everyday practices and collaboratively shaping meanings (Hyysalo, 2010): it was important to recognize practices in Fab Labs as co-constructed, novel, situated and evolving. As Bowker and Star (1999, 294) pointed out, in a community of practice, "the activities with their stuff, their routines, and exceptions are what constitute the community structure".

public during its Open Days. The Lab's trajectory included several phases and changes in personnel, as documented in paper 4.

The objective of the ethnographic research during this period was to determine the subjects' perspectives on socio-environmental sustainability (that is, what they espoused), individually as well as collectively; what issues in the Lab implicated environmental issues; and if or how these issues were noted and acted upon (that is, practice).[22] I therefore did not prompt sustainability-related discussion from the outset but probed it if it arose and prompted it after some duration if it did not. The data gathering in the first phase of the research (particularly when the Lab was being built and the operations being planned) aimed to cover as wide a terrain as possible for one researcher. Environmental sustainability issues were foregrounded, but the fieldwork and interviews aimed to gain as complete a picture as possible of what was involved in establishing a Fab Lab and then maintaining it: that is, what a Fab Lab entails as a "going concern" (Hughes, [1971] 1984), how ideology is shaped and how it is enacted. (How ideology can be seen being enacted in Fab Labs is illustrated in Figure 7, a typical situation of how peer learning was fostered in the Lab described in Kohtala, 2013). Design-relevant issues were of interest given my design background and arose naturally due to the design school setting. Extensive fieldnotes were recorded, on the spot and immediately afterward, that included reflections and potential interpretations (and noted as such).

22 This objective applied to the Lab that was the subject of paper 4, but also all Labs visited during the three-year research period including the Lab described in paper 3 (see Table 2).

I was not directly involved in activities (such as teaching), except when invited (to test machine instructions, for example, or give feedback on student projects). Nevertheless, I did not hesitate from becoming involved in discussions on site. Once my focus on environmental sustainability became known, as it would inevitably do, subjects would at times appear influenced by my presence and discuss topics or ask questions related to environmental concerns. When this influence was obvious, it was noted down. By the same token, I also spent much time in the Lab and with communities who visited the Lab such as the Waste-lab group described in paper 4, many of whose members I had already known as friends and project colleagues for years previously. Over time, my presence was eventually less noteworthy and therefore less likely to influence actions or discussions in ways that would significantly affect the data. In other words, according to the constructivist stance adopted in this dissertation, the assumption was that I would indeed influence events and the data gathering itself would not be 'objective', but full awareness was paid to this possible influence. Relevant reflections and observations were noted in the fieldnotes as completely and rigorously as possible.

FIGURE 7: Observing how ideology (in this case peer learning) is sanctioned and fostered. In a pattern observed regularly in this Lab, the manager first monitors the situation, judging if or when she should step in to help. When another user begins to offer advice to the other two users, she steps aside to allow this and moves away to another user in the Lab. Source: Stills from a video taken by the author.

I was not made privy to internal strategy meetings or documents, but other relevant public and internal documents were provided and I was able to probe issues in interviews. Issues that had been clearly discussed internally also became salient, as they arose unprompted in interviews and conversations among several actors in the same time periods. They became salient to me by being the same issues raised by a number of actors but also in repetitions in how they were presented and even phrased by different people. (These issues were topics I could subsequently pay closer attention to, with regard to how or if they were enacted.) The Media unit also had a great amount of material archived online, in the form of videos, photos, blog entries, newsletters and annual reports, that could be reviewed and reflected against the insights derived from the fieldwork and interviews.

During the research period of 2012 to 2014 I also visited 14 European Labs (as well as a makerspace and an open citizen biology wetlab), and I attended the FAB10 annual Fab Lab network meeting in 2014. Fieldnotes were taken in all circumstances.[23] Interviews were conducted at FAB10, during the site visits and when relevant people visited Helsinki (known experts, actors from other Fab Labs and the like). During site visits, most Labs I visited for a short period (such as an afternoon, for an interview), but I stayed for two or three days in several Labs (and in several cases in

23 supplemented by fieldnotes and interviews in two Labs in Iceland by Hyysalo in 2013 using the same interview guide used in the other Labs

Lab managers' homes). The research method could thereby be identified as a mix of participant observation and non-participant observation (Flick, 2009). The Labs were selected for several reasons: their explicit approach to environmental sustainability, as seen (or not seen) in communications and/or projects, and how important they appeared to be in the Fab Lab network. They were also selected to optimize diversity in sample, in their espoused focus (such as entrepreneurship, education or community engagement), their host and funding model (such as municipality-supported or founder-self-funded), and their life cycle (Labs of various ages and in differing phases of development). Extensive fieldnotes were made throughout, and the most important interviews, or interview extracts, were transcribed (with notes made on the remainder). The most relevant research material was then summarized in memos: that is, summaries of the main observations and reflections.

With regard to other maker communities studied at the same time, such as Waste-lab, I attended many planning meetings and public events, as time allowed. These communities tend to conduct their planning in deliberately open, transparent and organic ways. This means, for example, that planning a public event will be guided by a few key actors from the organization in question, but others participate, contribute ideas and volunteer for tasks physically present at meetings and/or by writing their ideas on a shared 'Etherpad': online software that allows anyone to write text into a shared document. Etherpads are convenient documents that capture aspects of these processes for later examination. Due to time constraints, I could not consistently and regularly follow these various sub-cultures but could retain some sense of their directions and issues via interviews and occasional monitoring of their digital communications (social media, Etherpads and so on), which were collected as digital documents in the application EagleFiler (thus preserving webpages that could later disappear). These data were summarized in memos (notes on the key observations), which served as secondary data sets in producing article 4. Due to practical space constraints in writing paper 4, most attention was reserved for the data related to Waste-lab and their direct interactions with the Fab Lab.

The primary data sets for paper 4 were analysed via open coding. This was supplemented with analysis and interpretation-enabling methods such as writing up empirically grounded narrative summaries (Miles and Huberman, 1994) and creating positional maps and diagrams (Clarke, 2005). The analysis process was also recorded in memos (here, memos in the grounded theory sense, as a research and analytic diary, recording, for example, coding schemes and key insights; Strauss and Corbin, 1998).

The analytical work also strived to understand the research material as comprising stages in the development of the Fab Lab: its trajectory (Strauss, 1993; Bowker and Star, 1999; Johnson et al., 2010), drawing from the approach of "biographies of technologies and practices" (Hyysalo, 2010). Such an approach enabled cross-comparison and triangulation of the different data sources. To this end, the research material was collated in what could be called 'master memos': collections of key themes and categories, illustrative quotes, analytical diagrams and open questions and concerns. Each memo focused on a particular stage in the Fab Lab's evolution (the analysis work also entailing identifying these stages), and key themes could thereby be tracked through the trajectory and cross-compared. These master memos were shared and discussed with my advisor. Finally, an extended overview narrative, a 'master narrative', was written up based on this work, shared with colleagues and discussed. The master narrative was also shared with the Fab Lab actors for respondent validation. Several factual errors were clarified in this process, but the respondents did not offer any comments or critiques of descriptions or interpretations nor highlight any crucial issues that had been overlooked.

The analysis conducted on the data gathered on the Norwegian Fab Lab (paper 3) followed the grounded theory axial coding scheme described in Strauss and Corbin (1998) and is thereby congruent with Symbolic Interactionist framing (Reynolds and Herman-Kinney, 2003; Clarke, 2005). The data consisted of fieldnotes on observations, conversations and interviews on a three-day site visit to the Norwegian Lab, as well as videos and numerous photographs. (In this context, the interview was conducted in the same conversation stream over several days with the subject: for the 'interview', particular, directed questions were asked according to my question template, while several hours of less directed conversation also ensued where the subject could dictate the topic.) The coding scheme could not set categories of discourse against categories of observed activity as an analytical strategy in this case, for two reasons. First, the visit was too short to warrant longitudinal observations, and second, also a key finding, there was very little making activity during the site visit. The coding scheme therefore set categories related to the main subject's rhetoric of ideology and myth-making against the projects and activities he espoused as favourable, grounded by the evidence in the data. The categories and the extracts from the data were tabulated for easy sharing with the co-author. As my co-author presented her categories in the form of short narratives, according to ethnographic tradition, it was instead an easier task to produce similar stories about my key themes, share them with my co-author, and then discuss the most relevant themes and their implications.[24]

24 As this data set was relatively small, the data was coded and tabulated manually. The coded documents were later fed into TAMSAnalyzer, an open source data analysis software application, to ease subsequent cross-comparison.

The fieldwork entailed a snapshot of time in the Norwegian Lab for me, which may pose limits to its generalizability and encourage speculation, but the key insights were corroborated in large part by the paper's co-author, who visited in a different year, different time of year and for a longer duration. Moreover, the article aims for a rich and situated description: to "accept, develop and use the distinctive expression in order to detect and study the common" (Blumer, 1969, 149).

The analysis process also provided "sensitizing concepts" (Blumer, 1969, 147-150; Clarke, 2005, 28) for the analysis conducted for the Lab in paper 4, and vice versa: the ongoing reflection and analysis coming from the longitudinal study of the Fab Lab in paper 4 also clearly provided footholds for articulating insights in paper 3. The Norwegian Lab was an important part of the study, as it was one of the first Labs in the world to be established (the first one in Europe), before the notion of a Fab Lab network even existed. It could thus be seen as an emblematic case (Gobo, 2004). When compared against other Labs such as the Lab in paper 4 (fledgling, university hosted, urban, full of designers and other differing characteristics), such a Lab can reveal something about the configurational (Fleck, 1993), "fluid" (de Laet and Mol, 2000) aspects to Fab Labs that lend them strength and latitude (Hyysalo and Usenyuk, 2015), even while recognizing that the sociotechnical assembly of a Fab Lab is arguably more challenging to investigate and cross-compare than the dissemination of the Zimbabwean bush pump or a photovoltaic light kit (Akrich, 1992; Akrich et al., 2002).[25]

25 This dissertation therefore did not pursue analysis of, for instance, digital fabrication technologies as boundary objects (Bowker and Star, 1999), despite the importance of the concept in Symbolic Interactionism.

Indeed, the definition of a Fab Lab repeatedly stressed by the main subject in paper 3, the Fab Lab Director, re-appeared time and time again, unsurprisingly, in the fieldwork conducted in the other European Labs (referred to in paper 4). It thus constituted a crucial category, the exploration of which entailed choosing Labs to visit on an ongoing basis (and not as a fieldwork plan at the beginning of the study), according to the principles of theoretical sampling (Glaser and Strauss, 1967; Strauss and Corbin, 1998).

How each manager and each Lab entity perceived its role in the coming 'revolution'; how the past played a role in the Lab's situated present, and what elements of the past were important in the trajectory; what images of the future were rallied in strategy work; and what elements were missing from all of these processes – all these factors contributed to how each Fab Lab defined itself. They also arose as crucial to the subjects' experience of 'sustainability' or indeed of its absence: environmental concern was intertwined with other ideological or practical aspects in each Lab in ways that developed dynamically, through interaction and changing circumstances, while affected by existing conditions and previous events. The accumulation of data from the various Labs and events thereby led to a constant reframing of the definition of a Fab Lab as well as the definition of 'sustainability'. This understanding led to the need to be more precise about the research question: the need to articulate how sustainability was instantiated in practice. In other words, in the course of the research, environmental sustainability had never been precisely relegated to 'mere' matter and energy, but the fieldwork and analysis process allowed (or necessitated) the research focus to expand beyond a simple conception of reusing components and materials (or using 'bio-materials') in Fab Labs – at times an explicit concern but most often an implicit issue that embedded itself in other aspects of Fab Lab ideology. How 'sustainability' is represented in Fab Labs is therefore elaborated particularly in chapter 5 and paper 4.

Paper 4 therefore built from paper 3 and insights gleaned from the fieldwork and interviews from other European Labs and maker communities. (See also section 3.4.) Key themes from these data sets were compiled into the 'master narrative' and 'master memos' that served as the foundation for paper 4 and empirically grounding the texts.

The objective of paper 2 was to gather information from well-informed "acute observers" (Blumer, 1969, 41), experts and active practitioners, in a workshop setting. The workshop was designed to combine strengths from Lead User Workshops (Herstatt and von Hippel, 1992) and Participatory Design methods (Greenbaum and Kyng, 1991). (The workshop organization is described in more detail in Hyysalo, et al., 2014.) The principal analysis scheme for the data gathered in the workshop employed Property Space Analysis, which is congruent with Symbolic Interactionism (Becker, 1998). In this sense, it operated in a similar way as the grounded theory axial coding scheme (Strauss and Corbin, 1998) employed in paper 3 served to expose and ground any compatibility and differences between discourse and practice. As explained further in section 4.2, the workshop was also designed to reveal differences between espoused attitudes to sustainability and expressed commitments to environmental sustainability oriented values and how these values might be enacted in practice. (See Table 1.)

TABLE 1: Differences in themes addressed by workshop participants. The property space revealed that the sustainability-oriented workshop participants discussed more conventional environmental issues in future digital fabrication (being especially represented in the 'Clear expression' cell) but did not engage with the more future-oriented technological issues raised by the other maker practitioners (represented in the 'Fully unrecognised cell'). The table rationale is fully explained in paper 2. Source: paper 2, Table 4.

Trends / Solutions	So	S1 ("implied" sustainability solution)	S2 ("expressed" sustainability solution)
To	**Everything else** no sustainability-relevant trends no sustainability-relevant solutions	**Implied solution isolates** FLOSS* HANDICRAFT	**Difficult to trend** SPACE PLANNING OBSOLESCENCE SUPPLY CHAINS EXPERTISE
T1 ("implied" sustainability trend)	**Not recognised, not concretised trends** CHANGES TO MASS PRODUCTION LOCAL PRODUCTION NANO-TECH ALTERNATIVE ECONOMY	**Fully unrecognised** DIY-BIOLOGY LIBRARY TOOL LENDING SHARED MAKERSPACES NEW EQUIPMENT (TECHNOLOGIES)	**Expressed only in solution** OPEN EQUIPMENT SHARED CRAFTSPACES
T2 ("expressed" sustainability trend)	**Not concretised trends** BICYCLES REPAIR CULTURE ALTERNATIVE URBAN ALTERNATIVE CONSUMERISM	**Unrecognised expression** BIO-REGIONS TOXICITY	**Clear expression** URBAN AGRICULTURE REDUCTION IN ELECTRICITY CONSUMPTION RENEWABLE ENERGY SOURCES BETTER MATERIALS RECYCLE REPAIR REUSE WASTE REDUCE WASTE

* free/libre open source software

In the course of the workshop, it was also evident how making encompasses a universe of discourses, given the range of themes promoting, for instance, handicraft and expressing strong criticism of digital fabrication, or promoting the innovation potential inherent in personal fabrication (Table 3 in paper 2). Even the research literature summarized in paper 1, the integrated literature review, appears to constitute its own universe of discourses, being so conceptual and propositional. The methods for conducting the literature review summarized in paper 1 are described in the paper, and it is further summarized in section 4.1. The purpose of the integrated literature review in this study was to map the existing research on distributed production: to develop an understanding of the existing environmental issues in digital fabrication as well as the various ways they can be examined and reported.

The various data sets collected during the doctoral research process are summarized in Table 2. The table also indicates how the data sets served the papers.

TABLE 2: Data sets in this dissertation.

	DATA SET	CONTENTS AND OBJECTIVES	DESCRIPTION AND METHODS	ROLE
	FAB LAB MAIN SITE			
FIELDNOTES, PHOTOS, VIDEOS	Dec 2011 – Mar 2015: 79 sets of fieldnotes	observations during building and set-up; observations during everyday routines; during university courses and student presentations; during special occasions (opening party, stakeholder workshops, strategy workshop etc.) (included ad hoc interview-conversations)	supplemented with audio recordings for back-up; fieldnotes were analysed using open coding, positional diagrams (Clarke, 2005), narrative summaries, and were synthesized into 'master memos' describing the various phases of the Lab	**primary data set for paper 4**
	1143 photos, 101 videos (about 5.5 hours)	documentation of Lab, events, student presentations, etc.	summarized in fieldnotes, videos transcribed where relevant and included in fieldnotes	
INTERVIEWS	2012-2015: 19 semi-structured interviews	Fab Lab actors (10 organizers and 3 users)	supplemented with audio recordings for back-up; average 1 hour each, transcribed (included some follow-up by email); transcripts and email texts were analysed using open coding; included in compiling of 'master memos'	
AUTHENTIC MATERIALS	2011-2015: documents and multi-media	internal and external communications, such as presentations, surveys, some key emails, meeting notes, social media posts, websites and photo/video archives	monitored regularly and often (at least weekly) and summarized in memos (i.e. summary notes); included in compiling of narrative summaries and 'master memos'	

	DATA SET	CONTENTS AND OBJECTIVES	DESCRIPTION AND METHODS	ROLE
	WASTE-LAB			
FIELDNOTES, PHOTOS, VIDEOS	2012-2014: 11 sets of fieldnotes	observations of Waste-lab project particularly during 2012 (funded by Media unit that year), where events mainly took place at Fab Lab site; observations of one follow-up event in Fab Lab at end of 2013, observations of one crucial planning meeting in 2014	supplemented with audio recordings for backup; fieldnotes were analysed using open coding, and were synthesized into 'master memos' describing the various phases of the Lab	**primary data set for paper 4**
	250 photos, 17 videos (about 28 minutes)	documentation of events	summarized in fieldnotes	
AUTHENTIC MATERIALS	2012: documents and multi-media, Waste-lab	meeting notes, webpages and blog posts, social media, Etherpads (shared, open and collaborative online planning documents)	monitored regularly and often (weekly or more) and summarized in memos (i.e. summary notes) synthesized into 'master memos' describing the various phases of the Lab	
INTERVIEWS	2012: 1 semi-structured interview	Waste-lab organizer	supplemented with audio recording for back-up; about 45 minutes, transcribed transcript analysed using open coding; included in compiling of 'master memos'	
FIELDNOTES, PHOTOS, VIDEOS	Feb 2012 – Feb 2015: Waste-lab and parent organization (non-profit arts association), 17 fieldnotes	observations during events and workshops outside of Fab Lab, observations and notes on discourse during lectures and discussion events, observations during planning meetings	supplemented with audio recordings for backup, fieldnotes summarized in memos (summary notes) but not coded key points included in 'master memos' and 'master narrative'	**secondary data set for paper 4**
	413 photos, 11 videos	documentation of events	summarized in fieldnotes	
INTERVIEWS	2014: 1 semi-structured interview	Waste-lab parent association member	supplemented with audio recording for backup, about 45 minutes; most relevant parts transcribed, the remainder summarized	
AUTHENTIC MATERIALS	2011-2015: Waste-lab and parent organization, documents and multi-media	meeting notes, Etherpads, webpages, social media posts (excluding Fab Lab events of 2012 and 2013)	monitored occasionally (e.g. monthly), summarized in fieldnotes and memos (summary notes) key points included in 'master memos' and 'master narrative'	

	DATA SET	CONTENTS AND OBJECTIVES	DESCRIPTION AND METHODS	ROLE
	HELSINKI MAKER COMMUNITIES			
FIELDNOTES, PHOTOS, VIDEOS	2011-2015: 22 fieldnotes	observations of maker events, maker community meetings, workshops, observations and notes during lectures and discussion events, including my own discussion events (2012)	supplemented with audio recordings for back-up; fieldnotes summarized in memos (summary notes) but not coded key points included in 'master memos' and 'master narrative'	**secondary data set for paper 4**
	about 950 photos, 60 videos	documentation of events and meetings	summarized in fieldnotes and memos	
INTERVIEWS	2012-2015: 17 semi-structured interviews	key actors and organizers in maker communities in Finland and abroad	supplemented with audio recordings for back-up; from 30 to 90 minutes each; most relevant parts transcribed, the remainder summarized	
	2014, 8 semi-structured interviews	maker participants in futuring workshop (members of local maker communities)	supplemented with audio recordings for back-up, about 30 minutes each; summarized key points included in 'master memos' and 'master narrative'	also qualitative data for paper 2
AUTHENTIC MATERIALS	documents and multi-media	meeting notes, Etherpads, webpages, social media posts	monitored occasionally (several times a year); summarized in fieldnotes and memos (summary notes)	
	OTHER FAB LABS, FAB LAB NETWORK			
FIELDNOTES, PHOTOS, VIDEOS, INTERVIEWS	2012-2014: Fab Lab (and makerspace) visits abroad, 23 sets of fieldnotes	visits of one to three days, observations of Fab Lab activities and conversations with managers and users (2 Labs in 2012, 2 Labs in 2013 by Hyysalo, 3 Labs mid-2014, 12 Labs and makerspaces late 2014)	supplemented with audio recordings for back-up; Norway Lab data coded, the remainder summarized in memos (summary notes) but not coded	**secondary data set for paper 4;** Norway data as primary data set for paper 3
	34 semi-structured interviews	interviews with Lab organizers, volunteers and users on-site (2 by Hyysalo using same interview template)	supplemented with audio recordings for back-up; on average 15-30 mins (some to 60 mins); key interviews transcribed, the remainder summarized key points included in 'master memos' and 'master narrative'	
	1065 photos, 9 videos	documentation of Lab and activities	summarized in fieldnotes	
INTERVIEWS	2012-2014: 13 semi-structured interviews	other Fab Lab actors (mainly organizers) and experts	supplemented with audio recordings for back-up, several video-recorded; key interviews transcribed, the remainder summarized in memos key points included in 'master memos' and 'master narrative'	

	DATA SET	CONTENTS AND OBJECTIVES	DESCRIPTION AND METHODS	ROLE
FIELDNOTES, PHOTOS, VIDEOS	FAB10, 2014: 7 fieldnotes	observations of international Fab Lab network meeting, including symposium, workshops and break-out sessions, and Lab presentations	supplemented with audio recordings for back-up, summarized in memos (summary notes) but not coded key points included in 'master memos' and 'master narrative'	**secondary data set for paper** 4
	about 425 photos, 27 videos	documentation of meeting and activities	photos and videos summarized in fieldnotes	
AUTHENTIC MATERIALS	documents and multi-media	Fab Lab network, FAB10, Fab Foundation and other organizations' meeting memos, external communications, websites, social media posts	monitored occasionally (several times a year, more often when warranted); summarized in fieldnotes and memos (summary notes)	

3.3 DEFINING SUSTAINABILITY

The question of how the construct of sustainability was shaped during the course of the research process leads to the important point of how or if it should be defined: a common problem when researchers examine complex environmental issues and attempt to articulate their findings. Due to the nature of the research questions and objectives, the research aimed to clarify how the research subjects themselves defined sustainability, especially recognizing how the definition of a sustainable solution and sustainable society will be a continuously re-evaluative, ongoing design and discursive process (Wahl and Baxter, 2008). Nevertheless, there exist highly informed conceptions of sustainability that provide stronger anchors as to what it may be and what it clearly is not. As an umbrella concept, the 'Brundtland' understanding of sustainable development offered some guidance (WCED, 1987). The common understanding that sustainability comprises three dimensions, environmental, social and economic, was acknowledged; not as equal pillars necessitating a balance among all dimensions, but rather emphasizing that it is the environmental limits that constrain society and the economy (Figure 8). Because many environmental issues are so intractably linked with social issues regarding sustainability, the term 'socio-environmental' has often been used in this dissertation interchangeably with 'environmental' even while environmental concerns are foregrounded.

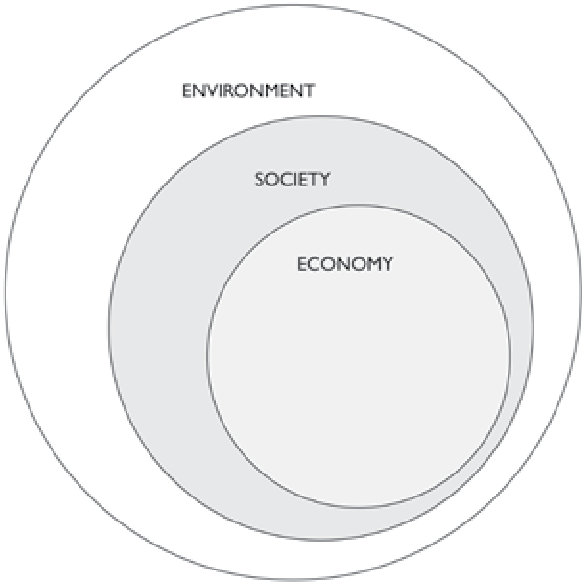


FIGURE 8: Conception of sustainability and its dimensions. Source: author, origin unknown; possibly derived from Daly et al., 1989.

For a more solid footing in evaluating socio-environmental sustainability, the Framework for Strategic Sustainable Development (FSSD) (Robert et al., 2002) developed by the non-profit organization The Natural Step was consulted. This framework provides sustainability principles, practical tools and evaluative checklists used in consulting and environmental management procedures. The Natural Step's framework is described as simplifying complexity by providing simple rules as sustainability principles; it is seen as a "source-oriented" paradigm that poses more stringent demands on processes of production and consumption than effect-oriented paradigms (that is, "estimating what nature can tolerate and then setting standards for emission and resource use") (Tukker et al., 2008, 19, 25-26). At the end of the first year of fieldwork for this doctoral research, a baseline analysis of the environmental issues in Fab Labs was compiled, presented at The Natural Step International's headquarters in Stockholm, Sweden, and discussed with these colleagues. The findings from the fieldwork, particularly the environmental implications, and drafts of the articles were also regularly discussed with my colleagues in the NODUS Sustainable Design Research Group.

3.4 RELIABILITY AND VALIDITY

The questions of reliability and validity in qualitative research have been much discussed, with scholars offering alternative criteria (Flick, 2009). Reliability of data and interpretations in such research is more a question of trustworthiness, pertaining to how data was recorded (Flick, 2009). In this doctoral research, care was taken with fieldnotes. The fieldnotes were recorded according to the same notation throughout; that is, specific punctuation and markings made apparent and distinct what were subjects' exact words, my descriptions of their actions and thirdly my personal reflections on actions and events. The fieldnotes also all included background information (such as what had brought me to the situation, what the space looked like, how it was organized and with what or whom I was expecting to interact and observe). Separate sections at the end of each note served as memos, for recording further reflections and possible interpretations, questions on which to follow up and personal emotions at the time. Interviews were conducted mainly according to pre-designed questions with flexibility to digress if it seemed warranted. The interview questions and topics were also cross-compared: they were reviewed subsequently and the questions updated for the next interview with the same subject as well as compared to topics and insights from other interviews. Several core questions were used across most interviews.

According to Flick (2009, 387), validity in qualitative research of this kind is tied to "how far the researcher's specific constructions are empirically grounded in those of the members". To ensure the validity or credibility of the interpretations, the findings and paper drafts were discussed regularly with colleagues in small groups and subjected to scrutiny in research seminars in the department. The formation of categories and their empirical bases were made transparent in a table for paper 3 (the Norway data set), and the key themes for the main Fab Lab data sets with their empirical grounds were summed up in the 'master memos' compiled for paper 4. The strategy of creating the master memos was also to ensure triangulation of data sources, which had been analysed via triangulation of methods. The 'master narrative' from which paper 4 was edited was shared with the Fab Lab subjects for respondent validation (as mentioned previously).

With regards to generalizability of findings, ethnographic research is marked by in-depth examination of often only one 'case'. Generalizability thus refers not to applicability of findings to a certain wider population, but what applies to the broader phenomenon (Gobo, 2004; 2011). Fab Labs represent a "deviant case" (Becker, 1963), meaning an alternative to the mainstream: a "subculture or emergent or avant-garde phenomena that could become dominant or significant in the future" (Gobo, 2004, 446). In this understanding, the findings are meaningful for understanding self-selecting, self-organizing groups working on projects collaboratively, where ideology and an *imaginaire* guide projects and action. Several Fab Labs were therefore observed, to see similarities and differences, as well as other grassroots maker communities. A Fab Lab in a university in northern Europe shares many characteristics with university Labs in the United States, in New Zealand or large cities in India; grassroots, self-funded Labs share many of the same concerns as hosted Labs. However, what makes them sustain will depend on how they interact with, react to, provoke or attempt to ignore their local environment: in these kinds of social groups, the relationship between their ideology and the conditions in which they find themselves.

As mentioned in chapter 2, section 2.1, the challenge in surveying Fab Labs, and determining appropriate sampling sites accordingly, relates to their rapid proliferation: amplifying the difficulty to access accurate information as well as physical access to Labs. The exponential spread of Labs has also meant an increase in their diversity: who founds them, who funds them and who uses them. Moreover, as previously mentioned, overviews and surveys cannot capture trajectories and how Labs change as their situations change; there is thus value in extended narratives that examine particular Labs more deeply and at different phases.

That said, in this study, due consideration was given to how the Labs selected for study represented the Fab Lab network. The Lab in paper 3 was clearly emblematic, significant in the history of the Fab Lab network and representing one in a later phase. The Lab in paper 4 was hosted in a university, and this was regarded as representative. As mentioned in chapter 2, Labs in the United States (as the original host country) tend to be "hosted" Labs (Troxler, 2014), and a review of Labs demonstrated that a large proportion of American Labs are hosted in colleges and universities (i.e. 30 out of 90 total).[26]

26 This is based on a review of 90 descriptions of active US-based Labs, on websites and the Fab Lab network's list (i.e. <www.fablabs.io/labs?country=us>, accessed 15 January 2016). Of these 90, 57 Labs are located in schools of various levels, colleges and universities.

In Europe, the network is more diverse. Universities are typical hosts, hosting, for example, seven of the 21 active Labs in the United Kingdom, nine of the 30 in Germany, and three of the seven Labs in Denmark. However, Labs in Europe are also hosted by municipal and regional actors: by cultural centres in the Netherlands, Belgium, and Denmark, for instance, and by innovation centres, in Iceland, the U.K. and Switzerland, for instance. Labs are also managed and largely funded by their own founders, either as a small business or as a cooperative association as a legal entity. (The latter appears particularly prominent in France.) Moreover ecology and environmental concerns are declared in some Labs' missions, though such explicit mentions are in the clear minority (about ten Labs of the total of about 280 Labs in Europe).[27] Field visits and interviews were thereby also conducted at three explicitly environmentally oriented Labs, one of which is run by a university; five entrepreneur- or artist-run Labs of different sizes and ages; a Lab in a municipal cultural centre; a municipal library Lab; two Labs hosted by a national innovation centre; an independent Lab in an arts organization; and a Lab hosted by a professional union. The key findings emerging from the main research sites could thereby be reflected against the data gathered in these Labs.

27 These figures are also based on the review of descriptions of active Labs in <www.fablabs.io/labs> in January 2016. Because of delays in updating information, ambiguities in information presentation and language barriers, the figures remain estimates.

The differences among Labs are therefore instructive, while rich, thick descriptions have their benefits, also for understanding other alternative social groups beyond the Fab Lab social world and the barriers these groups face. According to Becker (1998, 55), the specificities of a case are crucial: where something happens, and when, form its "environing conditions", and the researcher must be aware of how they have shaped the phenomenon she is now studying and articulate it. This requires being explicit about these local, situated and emergent conditions, determining what patterns can be identified, while acknowledging the role of rapid change and ensuring that "patterns of practice and outcome are … not seen as immutable" (Russell and Williams, 2002, 59.)

This chapter has summarized the research approach to understanding and articulating the socio-environmental potential of Fab Labs, as they seek to establish their role in democratizing production. The next chapter will summarize the papers and their key findings.

A workshop during WÄRKfest, Finland's first event for makers and hackers, Helsinki, October 2012. Source: author.

4

SUMMARY OF PAPERS

Before presenting the main findings and contributions of this dissertation, this chapter will present the summary of the papers. The original research papers are appended at the end of this introductory section.

4.1 PAPER 1. ADDRESSING SUSTAINABILITY IN RESEARCH ON DISTRIBUTED PRODUCTION: AN INTEGRATED LITERATURE REVIEW

Research on the environmental hazards and opportunities in distributing production is only now emerging, given the dominance of mass production. This paper summarizes the research findings as well as methods, implications and research gaps in an integrated literature review of 29 studies from diverse fields, which included research on sustainable mass customization as well as material peer production (whether it is called personal fabrication, fabbing or making). (Only 29 studies were found as relevant, out of a possible 9700 articles published by the journals surveyed.) While this dissertation focuses on material peer production practices, it is instructive, even necessary, to understand the relationships between these informal activities largely outside the market and the changes happening in industries as they move towards mass customization and other activities involving significantly more interaction with customers/users. (See Figure 2 in the paper; Figure 4 on page 29.) In one direction, developments in digital manufacturing equipment used in industry eventually impact the desktop models created for personal fabrication. In the other direction, fabbing and making are at the forefront of new sociotechnical practices that may mainstream; how environmental issues are understood and addressed at this level may ultimately impact developments at the industrial scale and provide the 'business case' for sustainability-oriented strategies.

Surprisingly few of the reviewed studies involved empirical data. Many articles remained conceptual and explorative, which indicates that, first, the phenomenon is new and evolving and, second, researchers appear uncertain how to even study the environmental benefits of distributing production. Part of the challenge lies in dealing with complexity and large system boundaries if one is, for instance, comparing mass production to distributed production. Methods such as LCA are therefore clearly limited, and the objectives of this review were to identify what other methods are or can be used and how various findings from diverse fields can be combined to gain a richer understanding of both environmental threats and opportunities in distributed production (or prosumption) patterns.

Based on the analysis of the literature, a conceptualization of distributed production could be created and visualized (Figure 4 in the paper and Figure 5 on page 38), where activities varied on a spectrum of, on the one hand, how much users/consumers were involved in the production process (i.e. a 'co-design' process very much in the hands of the producer versus non-hierarchical peer-to-peer production) and, on the other hand, the scale of production and production volumes. Based on this conceptualization, a summary of how the authors of the reviewed studies proposed environmental benefits to distributed production could be mapped (Figure 5 in the paper; Figure 10 on page 75). An often repeated proposition was that users who fabricate their own products (or are involved in its design or production in some significant way) will keep and use the product longer, forming a distinct attachment and experiencing a high level of product satisfaction that can combat our current 'throwaway society' conditions. Another often seen theme was the reduction of negative environmental impacts connected to transport emissions, as production would be done locally. However, as many of these studies were conceptual and not based on empirical testing, model testing or case studies in real life practice (or this testing/data gathering was not explicated in the paper), these environmental benefits remained propositions. Moreover, the ability to engage citizens in production, either in DIY fabbing and making or in 'co-designing' mass customization, appeared crucial to more sustainable production, but the connections were not well articulated in the papers. This gap was especially unacknowledged in the mass customization papers: customization and personalization of products were mainly seen as contributing to sustainability as in 'meeting user needs', but the very existence of the product from the outset was not questioned.

This may highlight the promise of the Fab Lab peer production model of invention with regard to material flow and possibly even the rebound effect, as users often create products that meet their own needs but do not exist on the market (von Hippel, 2005).

The literature was also less forthcoming on the potential environmental problems a distributed production paradigm can carry with it, and these issues remain blind spots in our understanding (Figure 6 in the paper). Among the most salient of these concerns was if distributed production practices will simply add to the material flow in current mass production rather than replace it, negating any claims that distributed production and peer production will dematerialize consumption. The claims about localizing production are also open for debate, as one paper in the review highlighted that in practice, mass customization production often occurs far from the customer (Chin and Smithwick, 2010). In material peer production, even if products themselves do not tend to travel (as designs do instead) (Birtchnell and Urry, 2013b), materials, components and equipment do often currently travel long distances and fabbed products made with higher quality processes or materials may be ordered from digital fabrication services located elsewhere.

The literature review therefore contributes to a better understanding of distributed production and its potential for and limits to mitigating negative environmental impact, as illustrated in the concept maps. It encourages relevant actors to take the findings into account when planning current and future activities, in production practice as well as in research.

4.2 PAPER 2. ANTICIPATED ENVIRONMENTAL SUSTAINABILITY OF PERSONAL FABRICATION

Fab Labs and personal fabrication exist in a rapidly changing sociotechnical environment where people and practices shape technologies, and new tools, techniques and processes shape people's actions and interactions on an ongoing basis. There is scant research literature on either these personal fabrication communities or the environmental issues implicated, and the empirical studies tend to be narrow technical and assessment-based exercises. We therefore know little about how makers engage with present and future environmental issues in makerspaces, even if they explicitly adopt pro-environmental stances. Such understanding would enable the establishment of guidelines, for instance, or activities to help makerspaces enhance their environmental knowledge and awareness; take steps in current practices to mitigate negative environmental impacts; plan future strategies that consider socio-environmental sustainability; and engage in discussion and reflection on how their actions may indirectly impact society and consumption patterns in future.

This paper summarizes the sustainability analysis of a one-day workshop conducted with a group of expert makers in Helsinki, Finland in 2013. The workshop was planned and conducted as part of the participatory planning processes of the Helsinki Central Library, engaging the local maker communities in identifying the issues relevant for a public makerspace in 2020. Drawing elements from both Lead User Workshops (Herstatt and von Hippel, 1992) and Participatory Design methods (Greenbaum and Kyng, 1991) in the workshop plan allowed us to gather highly relevant information for the library about future trends and solutions, but also enabled more iterative, long-term collaboration between the library and the various local maker communities, via ongoing codesign of an evolving real-life prototype (a pilot makerspace). The workshop method and rationale is further described in Hyysalo, et al. (2014).

A key objective of the workshop was to supplement our knowledge of the environmental issues in personal fabrication: if active maker-practitioners and experts identify the same issues as seen in the research literature (as depicted in Figure 1 in the paper and Figure 6 on page 39), what new issues they put forward, and what they raise and concur on as important. Moreover, the workshop structure and the analysis scheme enabled some identification of gaps between discourse and practice: participants could identify environmental implications connected with future personal fabrication issues, emphasize them as particularly important and solicit agreement, or pay no heed to these sustainability implications. They could express concern with the environmental implications of certain future trends and confirm this concern by also concretizing it in operational solutions; in contrast, not concretizing the environmental issues by proposing related solutions could indicate that the proposed trends were rather more on the side of visions if not wishful thinking. Finally, they could identify themselves as sustainability oriented and engage with and emphasize certain issues and not others. The analysis scheme, a "property space analysis" (Becker, 1998) or "logical property space", was thus used to compare these expressions in a Symbolic Interactionist compatible framework (see Figure 4 in the paper).

The findings of paper 2 showed that most of the practitioners, who were not considered particularly environmentally oriented, engaged unevenly with sustainability topics with the exception of those revolving around energy as well as principles of openness and sharing. The property space analysis also revealed a gap between two groups of practitioners, the makers identifying themselves as sustainability oriented and the other participants. The most technologically knowledgeable participants raised emerging issues such as new practices (around, for example, DIY-biology[28] or nanotechnology) and new tools and technologies, but they generally did not express any environmental concerns associated with these future possibilities. Nor did the sustainability-oriented participants engage with these issues or their implications, in their mission to consider traditional and imminent making practices such as material waste and reuse. In general, the sustainability issues that rose to prominence in the workshop were among the most obvious and apparent ones today, such as repairing and recycling (or reusing) activities in makerspaces as well as energy use.

28 DIY-biology, citizen biology, garage biology or biohacking are activities outside of conventional scientific arenas and laboratories exploring the life sciences and synthetic biology (Tocchetti, 2012; Delfanti, 2013).

In real-life practice, as reported in Hyysalo et al. (2014), the library stakeholder, for whom and with whom the workshop was conducted, was able to implement some of the findings from the workshop in their current prototype library makerspace, as well as begin to plan for other sustainability-relevant issues in the new forthcoming library: "These plans are partially attributable to the heightened awareness of the sustainability implications of and decisions on setting up maker spaces which the workshop clarified. Overall, the planners stressed that the workshop and further concretisation provided a clearer idea of which technologies and directions to monitor more closely and from whom to gain further insight as the planning progresses" (Hyysalo et al., 2014, 223).

Despite the finding in this paper that seemingly only 25% of the issues discussed in the workshop will have environmental implications in the near and far future, this real-life consequence affirms the benefit of dialogue on these issues with stakeholders and among makers. As concluded in this paper, shared events and facilities that bring the various maker communities together (and their varied knowledge bases) would foster ongoing dialogue on and assessment of socio-environmental issues in this rapidly changing field, especially if supplemented with guidelines and manuals that translate not-easily-accessible research findings into implementable actions in makerspaces.

4.3 PAPER 3. THE STORY OF MIT-FABLAB NORWAY: COMMUNITY EMBEDDING OF PEER PRODUCTION

In the far north of Norway, a pleasant road winds its way south of the town of Lyngseidet through a landscape of fells and farms. A rather undistinguished turn-off is marked by a more distinguished sign reading

'MIT-Fablab Norway'. The lane ends at a large, traditional Lapp log building that looks like a community centre or a rural dance hall.

This paper presents an ethnographically informed narrative on the Norwegian Lab, the first Lab in Europe and among the first in the world to be established. As both authors experienced the Lab founder's storytelling style to be a powerful tool in transmitting Fab Lab culture and vision, that of the individual Lab as well as the Fab Lab network, the voice of the main research subject impacted the analysis, the prioritization of themes and how they were presented in the paper's structure, as well as how the paper itself was written. As Charmaz (2002, 474) has pointed out, "When... authors present both the central idea and its major categories in vivid terms, they simultaneously integrate their analyses and engage readers in their theoretical renderings."

The paper aimed to address a lack in the research literature: examination of what actually occurs in Fab Labs and how organizers maintain their Labs as a continually evolving culture and social world. To our knowledge, the only research published on the Norwegian Lab has been a study of its role in its regional industrial community (Gjengedal, 2006). This paper is therefore positioned between these common research foci (among the relatively few studies on Fab Labs that exist): that of platforms and ecologies for innovation and/or open design (Troxler and Wolf, 2010; Paiva, 2012) on one end, and that of individual makers and the micro-actions of fabricating on the other (Maldini, 2013; Ghalim, 2013).

The narrative articulated the role of a charismatic community member in normalizing digital fabrication and Fab Labs in his region through a 'domesticating' of the space: a hearth, a kitchen, dining tables and beds dominated the space while the actual equipment was pushed to the back and sides. While the Lab had played a role in bringing key Fab Lab network actors together in the early days, there appeared to be a drift away from actual personal fabrication in pursuit of funding from, for example, local tourism projects. The domesticated Lab and its role as a community centre, hosting a myriad of community activities, clearly contributed to its sustainment as a place and meeting space but also appeared to fuel the shift away from actual making – accentuating the tension between the Lab's role in its local geographic community and its relationship with the rest of the Fab Lab network. This tension has been noted elsewhere in the Fab Lab community subsequently and regularly.[29]

29 See for example Zijlstra (2013) and Sylvester and Döring (2013).

Moreover, a Lab normalized by an identity as a community centre may be more readily supported financially by outside funders and stakeholders, who may otherwise find personal fabrication as an activity and Fab Labs as a space not easily classifiable and the benefits and Return On Investment not well articulated. Nevertheless Fab Labs (and other makerspaces and hackerspaces) are alternative spaces by definition: they rely on a conception of an open access, configuring and configurable space that is an alternative to existing, incumbent and institutional (usually hierarchical) structures in order to attract and recruit participants and inform strategy and action. A 'normalized' Lab may ensure funding from a wider variety of sources for a wider variety of activities, but this may also repel the very actors it was designed for initially. In this case, it can directly threaten the clear strength of this Lab as conveyed in the founder Karlsen's stories: the very diversity of participants and what they do together. This is a threat despite Karlsen's compelling imagery of a network society and the "network of brains" that form Fab Labs.

As economic sustainability is the dominant and ongoing concern of most Labs in the network (as also explicitly stated in this paper), the current state of this old Lab can shed light on the trajectory of younger Labs as they continue to seek funding and self-sufficiency. It is a single case but it is emblematic, being one of the oldest Labs still functioning today. (The other early Labs established in the period 2001-2004 still operating are the first Lab, the South End Technology Center in Boston founded by Mel King, and the Lab at Vigyan Ashram in India, founded by S.S. Kalbag. See Gershenfeld, 2005.)

That so little personal fabrication activity happened during both researchers' visits implicates the reflection and critical discussion Fab Lab actors need to have regarding the tension between serving the local community and the global network. That 'sustainability' in the Fab Lab network almost exclusively stands for economic sustainment and longevity means that environmental issues will rarely rise higher on the agenda. Explicit environmental orientation in projects could nevertheless be a clear opportunity for this specific Lab (and appeared to be occasionally but not consistently), which is otherwise proud of its socio-historical context and its beautiful, but delicate, landscapes. Environmental issues thereby become intertwined in the Lab's conception of 'sustainability' and the projects taken on, but they are not always explicitly discussed and addressed as such. This poses a challenge for all Fab Labs and how they see their role in their communities: from their maker community, to their local community, to society, also in future.

4.4 PAPER 4. MAKING 'MAKING' CRITICAL: HOW SUSTAINABILITY IS CONSTITUTED IN FAB LAB IDEOLOGY

The fourth and final paper examines a young Fab Lab in a university from its inception to growth and development, from the end of 2011 to the beginning of 2015. It is valuable to study Labs in the initial phases of their trajectory (Strauss, 1993) – where the bulk of decisions on practices and infrastructure are made and pre-configured for some time to come (Hyysalo, 2010). Such knowledge complements knowledge on Labs' later phases, as in paper 3 – where the results of series of reconfigurations arguably become visible. The key actors in this narrative were the administrators and decision-makers running the Lab and the key focus their interactions with the community of users and the niche group of users who explicitly aimed to explore ecologically oriented solutions. Important data sets included the digital fabrication courses that university students could take for credits, which served as the platform for transmitting Fab Lab culture (peer learning, self-sufficiency and user diversity) and principles of design for digital fabrication. While the network is growing too quickly to have accurate statistics on types of Labs established and planned, a great many Labs are set up within universities, and within media study programmes, making this Lab a typical, representative case.

The analysis particularly focused on how decisions were made and what was prioritized. Ideology and vision creation entailed long and intricate processes, shaped as they were by a number of actors migrating in and out of the Lab (in comparison to the story in paper 3 that was limited to mainly one dominant local organizer representing the history). Observations of actions and practices revealed clear challenges in enacting espoused values, and this was most readily articulated via materials and material artefacts that carried meanings and intentions. The wealth of things to juggle in the Lab, the questions that needed to be addressed and the 'fires' that needed extinguishing (sometimes literally, given the heavy use of the laser cutter), the tension between establishing new practices and adapting to existing routines and infrastructures in the university; the weight of the everyday was ever in danger of drowning ideals. Invisible issues (such as material waste) became even more invisible in such a situation, and shortcuts to save time also cut short envisioned worthy projects.

The analysis was buttressed by Pfaffenberger's (1992) notion of technological dramas: the Lab was clearly a "countercontext" where artefacts such as digital manufacturing equipment were appropriated and reconstituted as open access tools for invention and production. Here other voices rose to prominence: critical voices, alternative viewpoints and action pathways from other Fab Labs, and ideological concerns as presented in the FABx events. Such mixed messages did not appeal to some communities with potential to help the Lab enact ecological ideology: they neither wanted to engage with the space nor with what they felt 'design' represented.

In comparison to the Norwegian Lab presented in paper 3, the key to sustainment and longevity in institution-hosted Labs (Labs that are located within and funded by bodies such as universities, museums, municipalities and libraries) (Troxler, 2014) is connected to proving its worth: what a Fab Lab is for in terms of community and societal responsibility. Independent, self-funded and entrepreneurial Labs, in contrast, must sell services to survive, but simply selling printing services compromises their ability to offer open access. In short, it compromises their rationale of being a Fab Lab. Both types of Labs must struggle against the tide of becoming "just another printing service".

In this Lab, open design was seen as the key to what the Fab Lab was for, its role in its community and sub-worlds, and the paper links the Lab's commitment to open design as also key to how sustainability could be integrated with its identity and practices. In this understanding, open design, as practiced in this Fab Lab and fostered among its users, would allow strategic thinking as well as ad hoc and contingent responses in building a designer's resilience in an uncertain professional world. Open design also acts as a metaphor and guiding vision for how Fab Labs can empower their local communities and enhance their ecological resilience, combining the skill to think conceptually and plan ahead with the ability to act locally and appropriately: working within resource limits and according to situated conditions.

The paper therefore aims to articulate the often hidden dynamics in how a social group such as a Fab Lab carries out its work: a group that involves formal institutional structures, modes of governance, and missions and visions defined hierarchically (the university in this case), working in concert or in tension with a peer-to-peer operating mode that is emergent, heterarchical and explicitly defined as "open" and enabling. The paper also has a practical aim, to encourage further dialogue in the Fab Lab network and awareness (especially among new Fab Lab organizers) of the ongoing challenges they will encounter in enacting ideology. The diagram in Figure 5 in paper 4 (and Figure 9 on page 73) reminds these actors that Fab Labs do exist as a result of past events and their decisions and actions have consequences beyond their walls. Creating a clear vision and reflecting on actions can help Fab Labs avoid the fate of becoming just another printing service.

An open day 'regular' (left) discusses his project with the Fab Lab manager (right) in FabLab Breda, the Netherlands, November 2014. Source: author.

5

CROSS-CUTTING CONTRIBUTIONS

This chapter will sum up the most important findings and highlight the main cross-cutting contributions of this dissertation. Practical implications will also be discussed as they arise, while the final chapter will sum up the implications and final conclusions.

The first contribution of this dissertation has been to highlight that there clearly *are* environmental issues in digital fabrication and distributed production, as well as opportunities to diverge from the harms of mass production. Fab Labs appear to need help in identifying and implementing actions. The second key contribution, related to the first, highlights and confirms that in these material peer production communities, current concerns predominate – no matter the espoused ideology and expressed commitment. Actions taken by different communities appear contradictory to ideological rhetoric, issues easily remain invisible, and digital fabrication tools and their community-space ensembles thereby engender controversy over their meanings and intent.

Building on these two contributions, the third key finding thereby illustrates how the materials in Fab Labs represent discourse and how they mediate access and participation. Most crucially, the research shows how socio-environmental sustainability issues are interwoven among the other ideologies espoused via material objects. This interweaving is situated and 'context-dependent', but its explication helps identify opportunities for and barriers to more sustainable practices. This contribution to knowledge on peer production serves the Fab Lab community, but also the wider material peer production research arena, research on Sustainable Consumption and Production and research on sustainable innovation. Building on the third key finding, the fourth contribution focuses on the design-relevant opportunities identified in the maker communities researched. This articulation contributes to a better understanding of how design, designing and designers can participate in the sustainability discussion and implementations amidst potentially radically shifting production and consumption patterns. This sets the stage for further experiments and research foci that can continue to document this rapidly changing phenomenon.

5.1 CONTRIBUTION 1: ENVIRONMENTAL ISSUES AND ACTION

As stated, there are clear practical environmental issues in Fab Labs and the maker movement that should be addressed, first, for the health and safety of the people working in these environments and secondly, to be able to mitigate the negative ecological impacts on an ongoing basis. Two key areas to address (the 'low-hanging fruit') appear to be toxicity and energy (Drizo and Pegna, 2006; Huang et al., 2013; Olson, 2013; Stephens et al., 2013; De Decker, 2014; Short et al., 2015). More information is needed in Labs on material and process toxicity. Material safety and data sheets, MSDS, could be posted in Labs, for instance, and discussed in training and induction sessions, along with clearer information on emissions and impacts of other materials, electronic components and the processes of working with them. Given the increasing critical attention paid to energy-hungry digital fabrication tools, Fab Labs could promote the energy-efficient aspect of shared use, but also pay closer attention to daily electricity consumption: encouraging better troubleshooting and problem prevention, combining jobs, powering down, explicitly choosing green energy sources and so on. In-house solutions for production waste also appear to be spreading, as more Labs use RecycleBots, FilaBots and other devices for converting 3D printer waste into new filaments. Such solutions could be shared in the network to encourage their widespread use, and other in-house inventions may be applicable in other contexts outside of personal fabrication. These practical issues and potential solutions relate to the tangible material flows as presented in Figure 9 (which appeared as Figure 5 in paper 4): conscious attention to the materials, equipment and components coming into the Lab and the waste and other tangible outputs.

Other tangible Lab outputs involve what artefacts are produced and what projects Fab Labs decide to promote. Fab Labs and makerspaces may prove to be the ideal testing ground for solutions that are best distributed and localized rather than under centralized control. Low-tech energy

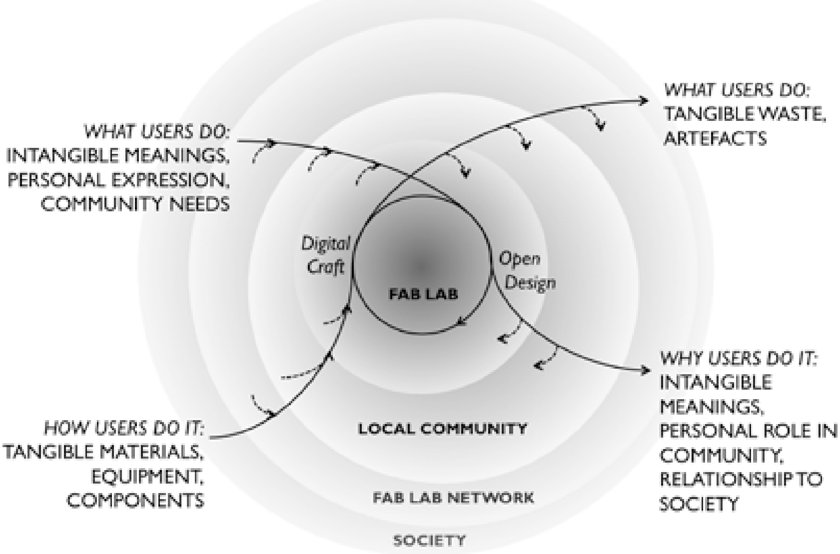


FIGURE 9: Understanding the situatedness and consequences of Fab Lab activity. Source: paper 4 (Figure 5).

technologies are the most obvious example (Hielscher and Smith, 2014, 44), wherein Fab Labs can be seen as an innovation intermediary (Stewart and Hyysalo, 2008) facilitating both experiments with renewable energy solutions as well as discourse on the issue (see Rohracher, 2003; Hyysalo et al., 2013). Other topics could be explored (such as building materials and sustainable food production, as seen in Valldaura Self-Sufficiency Lab and FabLab Amersfoort) and – in so doing – better documented for the benefit of both practitioner-makers and policymakers. Such shared information, in the form of manuals and guidelines, could include best practices in reuse, recycling and energy conservation; the environmental implications of material choices; and even the environmental and social consequences of the equipment and components, their manufacture and distribution (for example, the reality of the labour conditions under which electronics components are produced as well as disassembled, as indicated by Turner, 2006).

Such solutions, however, face clear implementation barriers that have also been articulated in the course of this dissertation: Labs may wish to share eco-relevant information and solutions for themselves and others, but this does not guarantee the sharing nor the take-up of these solutions (paper 4; Wolf et al., 2014). Research on environmental, health and safety issues is difficult to access and even more difficult to translate into daily actions and manuals and guidelines. Lab managers lack the time to find environmental information and may lack the competence to act on it (papers 2 and 4). They may also lack motivation if environmental values are not prioritized: environmental awareness and responsibility does not appear to be an explicit or inherent aspect of Fab Lab ideology, when compared to some other sociotechnical movements (paper 4; section 5.4 below). When even principles that are clearly espoused in Fab Labs, such as open access, are compromised in everyday routines, it is clear that individuals aiming to prioritize environmental concerns will also encounter challenges in enacting their values, due to funding, people migrations, time constraints and other similar structural barriers (paper 4; section 5.2 below).

Sustainability is itself a going concern and a moving target, necessitating a continuous, generative dialogue and reflection on what it means to Fab Labs in all its dimensions (environmental, social and economic) – especially given the rapid development of technologies and materials. To benefit from the high expertise and competence in the Fab Lab network, this understanding is likely best constructed in ongoing dialogue between the most expert (in technological terms) makers and eco-committed makers (paper 2). The challenge to bring these groups together, to engage a diverse range of participants will remain, as will the lack of time, but regional events and regional Fab Lab networks offer potential for such meetings of minds. Those Labs whose vision is most clearly socio-ecological already offer an inspiring role model to Fab Lab individuals and groups (paper 4). This may mean they are also best placed to spur on practical activities: co-created manuals and guidelines, as mentioned, but also promoting more communications inside and outside the network. To counteract the negative criticism that Fab Labs in the global North are mere hobbyist spaces for a homogenous elite, there could be more stories and narratives on how Fab Labs are contributing to a sustainable distributed economy paradigm: engaging in research and with researchers, building on our current understanding as illustrated in Figure 10, and articulating how environmental concerns intertwine with the existing concerns of education and entrepreneurship.

As mentioned, these are recommendations that are simple to suggest and problematic to implement. Further discussion on the kind of scaffolding needed in these novel peer-to-peer communities will be discussed in chapter 6 after discussing the other research findings and contributions.

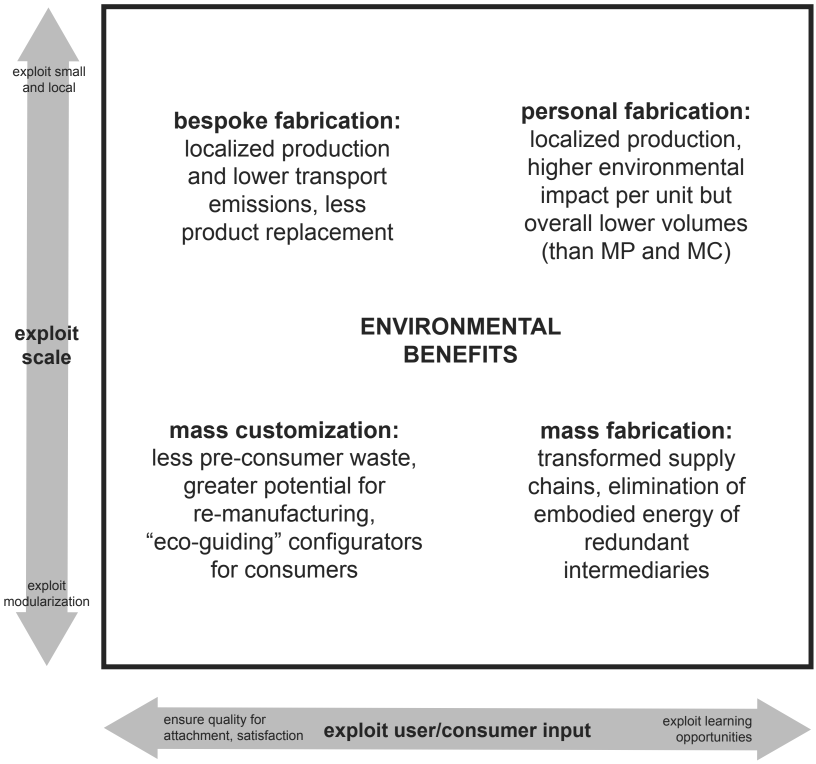


FIGURE 10: Summary of environmental benefits of distributed production in current research literature. Source: paper 1, Figure 5.

5.2 CONTRIBUTION 2: SALIENCE OF CURRENT CONCERNS

The current doctoral research clearly illustrated how Fab Lab actors find it challenging to enact ideology: how current concerns come to predominate and render some issues invisible, necessitating constant vigilance, and, in concert, how the abstract nature and ambiguity of ideology and discourse do not lend themselves to action plans but instead easily inspire controversy and critique. These dynamics are made visible by examining the material objects in interactions; this was described in paper 4, and more examples will elaborate on this point in these sections.

Based on the fieldwork and interviews conducted for this dissertation, it was evident that – in a nutshell – Fab Lab managers are extremely busy and they need to wear many hats. They thus need to consciously schedule in time for discussion on strategy, reflection on vision, work on action plans, not to mention activities to maintain their own skills and learning. Many know they benefit from the Fab Lab network and communicate via the 'polycom' video-conferencing system, regularly turning to their colleagues globally for advice and support, while others are less well connected and may not have attended the Fab Academy. They know that they would benefit from attending the regional Fab meetings but struggle to find the time. Some managers have been able to build up a roster of reliable volunteers and/or interns to help them assist users, while others struggle and still others are restricted from using volunteers (for instance, for insurance reasons in a highly regulated environment such as a university). Many managers want to strengthen connections to geographically neighbouring communities, but they find it challenging and their efforts inconsistently successful. The most persistent (and well-known) challenge is 'documentation': Fab Labs want users to document and share their work (and users want to too), but this is not happening to the extent desired (Wolf et al., 2014).

All this is widely recognized in the Fab Lab community. However, given the fanfare around 'revolution', what may go unremarked is how existing constraints (institutional regulations, professional expectations, personal ingrained habits and the like) serve to temper the revolution: the novelty of Fab Lab practices. As stated previously, little attention is paid (by researchers and Fab Lab actors alike) to routines and routinization, rendering Fab Labs as black boxes even to insiders.

To borrow Troxler's (2014) classification of grassroots and hosted Labs, Labs that are hosted by institutions (such as universities) are especially subject to others' routine arrangements and structures. As seen in paper 4, the studied Lab's procurement procedures were largely *not* dictated by strategies to foster local, neighbourhood collaboration (or even local economies), nor prioritize locally available feedstocks (cf. Rifkin, 2014), but rather by convenience: suppliers already in the host university's supplier list and/or MIT's inventory. An open source CNC mill had been built collaboratively in the Lab, but subsequently the mill remained unused. A year or more later, a large ShopBot was purchased, but it has been so difficult to use that the Fab Lab managers must monitor and direct its use, thus compromising the open access and self-directedness so valued they are embodied in the Fab Charter. In contrast, another Fab Lab described in paper 4 has been able to routinize its material choices, embedding environmental consciousness in its procurement regime (that is, completely restricting use of toxic materials such as the locally produced MDF as well as imported MDF implicating transport emissions).

Grassroots Labs have fewer institutional constraints and can establish their own procedures in their own ways, even while the actors come from their own backgrounds and conventions. The problem grassroots Labs face in securing financing can easily override everything else, including espoused commitments, values or manifestos. (This is clearly the case in hosted Labs too.) Routines may become established based on a particular individual's repetitive activities (which become repetitive in the interest of time-saving and efficiency) (Strauss, 1993). This is problem free except when the routine comes into conflict with espoused values, especially when this pre-configures conditions and infrastructure for future actors. One Lab manager, for instance, expressed concern about his colleagues, who were content to have users simply reproduce existing designs in order to learn the tools and processes; he would instead have preferred to spend the extra time encouraging users to learn to design for digital fabrication as well as learn to print. In the course of this research, other Lab managers have observed how peer learning culture is first (and perhaps best) learned in the Fab Academy and how a healthy peer learning culture frees up the manager to attend to more crucial duties in the course of a day (see Figure 7). Managers who do not consider the how and why of peer learning find themselves compromising and in a negative trajectory: spending all their time helping users instead of helping users help themselves. This negative trajectory extends to other aspects of Fab Lab ideology.

The concern about shortcuts, value compromises and inability to actualize visions also emerged in various trade and mass media channels during the course of the doctoral research. One opinion piece in an academic forum, for instance, expressed concern about how education was being practiced: rather than prodding creativity and learning by making unique pieces, children in observed makerspaces were merely printing out rote objects following "prescriptive instructions" (Pinto, 2015). Given the high importance placed on Fab Labs' role in education (Millner and Daily, 2008; Dlodlo and Beyers, 2009; Blikstein, 2013), this presents a challenge. Labs (especially new Labs, and Labs new to education) may need to be reminded that activities and interactions (and their consequences) should be considered consciously, regularly reflected upon and critiqued. An instructive example in a German Fab Lab illustrated this consciousness:

> Among the most important achievements of digital fabrication technologies is its implementation of objects of personal need that are not covered or beyond the reach of the mass market. Therefore, we want to preserve this important aspect, giving children the possibility to make something of personal use they might not get elsewhere. Within the scope of the workshop modules, they work on individual projects rather than repeating predefined tasks. (Posch, 2013, 66)

Routines (such as assigning users learning tasks or ordering equipment) are helpful and structuring – when they do not go unexamined and question the Lab's core reason for being. They thereby communicate both internally and externally what the Lab prioritizes. The objective in these paragraphs is not to scold or praise these individuals, makerspaces and their decision-making, but rather to highlight and make explicit the daily choices actors in Fab Labs must all make and how contingencies (situated interactions and conditions at that particular time and place; Strauss, 1993, 36-37) conspire and congeal into compromises they might otherwise not have made. Over time these compromises accumulate, but we may not be conscious of how. Such entropic patterns are by no means exclusive to material peer production communities, but the strong role of ideology in new making practices may be particularly concealing of what actually happens.[30]

30 Alongside the education example described above, it is also instructive to briefly examine another highly valued activity, the desire to promote micro-entrepreneurship. A recent Wall Street Journal article headline read, "3-D Printer Users Opt for Trinkets: Fab Labs Looking to Foster the Next Entrepreneurs Find Many Users Just Want to Make Doodads" (Hagerty, 2014). The article went on: "... many of the people drawn to these shops are using them to make art or trinkets, rather than launching businesses. ...'Entrepreneurship has been hard and elusive,' said MIT's Ms. Lassiter. Leaders of an association of U.S.-based Fab Labs at a recent meeting established a task force to spur more entrepreneurial activity..." (Hagerty, 2014). There are no easy answers here for Fab Labs, but discussing solutions is, as seen here, likely best accomplished in the distributed regional networks rather than as a solution-for-all. The issue nevertheless illustrates that goals and visions do not simply manifest.

In Figure 9, these issues are reflected in the intangible flows of meanings: why Fab Labs think they exist, why people become involved in personal fabrication, and how Fab Labs can serve the communities in which they are located. The Fab Lab projects that are regarded as most successful are those that can be seen as democratizing, distributing of agency and enhancing capabilities, and locally relevant. To repeat, these meanings and intentions may be intangible, but they become clearly visible and represented, intentionally or unintentionally, in tangible objects in a Symbolic Interactionist analysis. This will be discussed and illustrated especially in section 5.3.

Preoccupation with current concerns and time constraints was thereby a persistent finding in the ethnographic research findings from several Fab Labs, where practical duties dictated priorities, activities and decision-making to the extent they could eclipse other values. The phenomenon of issue salience and attention was even (rather surprisingly) observed in the process described in paper 2, the workshop. As described in the summary in section 4.2, it was found that the makers in the study were well able to envision the future, but their coverage of environmental issues was uneven. A key influence appeared to be participants' current projects. I knew, for instance, that several members of the so-called 'sustainability faction' (the self-proclaimed environmentally oriented participants in the workshop) had been long engaged in issues related to urban agriculture and horticulture, 'guerrilla gardening' and the like: a sub-community (or communities) who uses maker philosophies to devise and share designs related to self-sufficiency (for instance, Thomson and Jakubowski, 2012). All members of this group were also heavily involved in issues around waste, reuse and recycling: organizing regular 'fixer' repair events (Thompson, 2013);

excursions to recycling-relevant field sites such as waste sorting stations; and artistic and activist events around the topic. Nonetheless, this group contributed only two trends related to urban agriculture, while the solution of a greenhouse (as a solution a library makerspace might be interested in considering) was contributed by another workshop participant. Both collections of trends and solutions contained a notably heavy proportion of ideas that clearly related to waste reuse and recycling, a great many of which were contributed by the sustainability faction. As the workshop was held in February in Finland, and not during growing season, the sustainability faction at that time thus appeared especially preoccupied with their monthly 'repair café' events. This may account for the abundance of repair- and waste-related items and the neglect of other less familiar – but no less important – issues that had been raised by other workshop participants. These issues included the development of hybrid fabrication technologies (that would allow, for instance, the embedding of electronics during printing), citizen-led biology experiments in Fab Labs ('DIY biology'), and the introduction of nano-materials into personal fabrication, all issues that have unknown environmental implications with potentially great impact. Even the most 'obvious' ecological issue of promoting renewable energy in Fab Labs was mainly discussed by the other workshop participants.

Furthermore, some of the sustainability faction in paper 2 also expressed strong critique of digital fabrication and the Fab Lab, aligning themselves with a certain traditional and DIY maker ideology or identity. They, like the Waste-lab group members in paper 4, refused to engage with the topic of digital fabrication and, further, its potential to contribute to ecological solutions and sustainable communities. In this case, it can be stated that the strength of their own ideology combined with the salience of their current projects fostered a certain blindness to other potentials. They not only kept themselves suspended in their own reality, their social sub-world, they maintained the invisibility of the Fab Lab's environmental issues by refusing any accountability for them.

5.3 CONTRIBUTION 3: THE MATERIALITY OF IDEOLOGY

In the course of this doctoral research, in both fieldwork and interviews, several material objects arose as salient and meaning-carrying. Often this was because the actors themselves drew attention to issues of importance via the objects (such as Karlsen drawing attention to the kitchen in the Norwegian Lab in paper 3); at other times the objects seemed to embed frustration and annoyance, representing postponed tasks, ideal projects not yet realized, and similar problems for which a solution had not yet been found. The third contribution of this dissertation has thus been to clearly illustrate the process of discourse-making, and the dialogue between discourse and practice, becoming materially represented.

Many objects in the Fab Labs studied represented interactions with other social worlds. The glass bowl that had been mouth blown into a fabbed mould described in Kohtala (2013) is one example of how handicrafts embedding long traditions and distinguished skill mastery may be exalted in Fab Labs: one facet of the bits-to-atoms mythology. The other social worlds or sub-worlds may also be geographically apart. As stated earlier, the relationship with the global Fab Lab network is often espoused as important, and its role can be analysed by observing the use of the polycom system. In the Norwegian Lab (paper 3), as well as in the Lab described in paper 4, the video-conferencing systems symbolized much more than a technological communication channel. In Norway, the system often displayed webcam feeds from other Labs in the global network (and Karlsen chatting to Labbers in Iceland, for example) during my site visit, rendering the network and relationships with other people and Labs visible and explicit. The system also stood for other relationships, as Karlsen described: the ability to support distance education for local students in this remote region following university courses conducted further south. In the Lab in paper 4, other Labs' webcams were also shown from time to time, and the system was used for the participants attending the Fab Academy. Three Lab employees had attended the Fab Academy as well as FABx meetings, and two had worked in other Fab Labs. However, once these employees left the Lab, the new employees used the screen to play music on a digital jukebox and for teaching, but they did not have access to the resources nor sociality of the network. The existence of the network via Lab webcams was thereby not visible, to the Lab organizers nor to users. Lab managers in other northern European countries, in contrast, reported in interviews how valuable they found the polycom when needing technical support, for instance: being able to pose a question to Fab Labs online via the polycom and receiving prompt advice.

Lab culture and values are also conveyed in other material artefacts in the space, and even via the space arrangements themselves. These choices (or defaults) thereby convey other implicit information regarding priorities and time constraints. Furniture, display shelves and storage systems may be bought (new or used), made from appropriated objects or fabbed in the Lab, as illustrated in Figure 11. There are clear environmental messages in these objects too: whether a second-hand piece of furniture is recruited

FIGURE 11: Fab Labs (in Finland, France and the Netherlands) and their accessories. Source: author.

into the Fab Lab space; how an object may be appropriated ('hacked') and turned into another object (Figure 11, centre right); or if new, mass-produced objects are purchased in lieu of custom objects being made onsite due to time constraints (as was the case with a long-bemoaned bookshelf in the Lab in paper 4).

Paper 3 in this dissertation also highlighted how values, priorities and ideology were clearly visible in the layout of the Norwegian Lab: conviviality and sociality predominated, carried through in the material medium of the tables and chairs, hearth and kitchen. The layout of the Lab in paper 4 is not discussed, but it devoted much floor space to large tables and chairs for working on projects as well as more formal teaching situations and presentations. Space for handwork (such as more conventional woodwork) shrank or disappeared when the large CNC milling machine was installed, but later a high table for such work was placed in the storage room, which was arranged more efficiently to accommodate other activities and facilities. Near the end of the research period discussed in paper 4, the organizers were considering adding a sofa to create a more inviting, casual atmosphere and improving the display fixtures for a more educational and inspirational presentation of fabbed projects. Makerspace design can therefore both reveal what its organizers value as well as shape future interactions and activities. A typical Fab Lab space, how Fab Lab managers organize work, display and storage, is seen in Figure 12 below.

Paper 4 especially aimed to articulate how the environmental issues in digital fabrication are intertwined in other issues in Fab Labs. Printer filament waste in Labs does not only represent wasted natural resources (and Lab finances): it becomes intractably entangled in issues that impinge directly on espoused Fab Lab ideology, extending beyond simple 'ecological concern'. It can symbolize user time and frustration (thus feelings of satisfaction and accomplishment versus lack of 'empowerment'); technology design decisions (thus feelings of estrangement from the very tools of 'liberation'); recycling (thus symbolizing dependent or independent relationships with existing infrastructure and institutions); materiality (from the aesthetics of plastics to concern about Peak Oil); and so on.

In other spaces such as hackerspaces, 'waste' such as reclaimed electronics components are a valuable resource, a source of inspiration and a symbol of independence from the proprietary technologies from whence they came, thus directly representing identity in this counter-community (Toombs et al., 2014). In Toombs et al. (2014)'s study, while not articulated directly as symbols or an issue of visibility, the identity of the hackers who could use the discards and waste in the rather messy hackerspace was strengthened

FIGURE 12: FabLab Maastricht in the Netherlands.
Top: As 3D printing experiments are important in this Lab, the display shelf is of some importance, as well as space for using and building 3D printers. Bottom: Organization of 3D printing waste by colour and type. Such a visible and convenient system likely encourages filament recycling. Source: author.

by this ad hoc reuse, as well as the skills they needed to accomplish their projects with these materials successfully. The waste materials not only served to dictate designs, but they mediated identity. In fact, the question of materials, how they are stored and what practices these arrangements afford in turn leads to the compelling issue of how the space itself is designed and configured, as mentioned previously.[31]

31 This is a topic that has been little explored as yet (Hynes and Hynes, 2014; Saint-Clair, 2014), and one that will not be further elaborated in this dissertation, but it is a potentially fruitful avenue of discovery for future research.

In paper 4, the waste materials were reconfigured as usable when placed visibly and conveniently in a plywood box beside the laser cutter (Figure 3 in paper 4. See also Figure 12 on page 83). The off-cuts from the milling machine and laser cutter also carried multiple meanings. For the first Studio Master, they represented creative projects to reuse the waste that she had enjoyed in the past, but now had no time for due to the stress of establishing the Lab and attending the Fab Academy. For the Electronics Studio Master, they simply represented clutter, inadequate space organization and inadequate furnishings, a problem that again needed time to address. For the stand-in Studio Master, they represented an environmental problem that was nevertheless an opportunity for inventive reuse and a positive and responsible task for a Fab Lab to tackle, if and when time allowed. For myself as researcher, as well as some of the Media unit staff members who made occasional comments, the waste symbolized supply chains and end-of-life recycling systems outside this social world.

These examples illustrate how matter matters. The objects discussed are more than mere material and spaces; they are ideology (partly) materialized or material evidence of ideological compromise. Such materializations of ideology and ideals can convince actors the *imaginaire* is a project worth pursuing and animate them into action (Hyysalo, 2010, 75). This is so even if the *imaginaire* is itself never realized or completely materialized: indeed, it is its very incompleteness that keeps possibilities open and inspires and motivates people to act and participate (Hyysalo, 2010, 79; Gregory, 2000, 175-177).

How, then, was sustainability materialized in the Norwegian Fab Lab? In the course of the fieldwork reported in paper 3, Karlsen and I discussed the importance of economic sustainability as well as the sheer impracticality to differentiate environmental from social and economic sustainability dimensions: "Absolutely. It is impossible to separate them. And they are so tied up in so many ways; if you say sustainability, that gives the whole project a very wide responsibility, for other people, for friends, for enemies, for the economy, for local communities, counties, countries, for the global network," said Karlsen. This statement (which avoids talk of, for example, natural landscapes or biodiversity) reaffirms Karlsen's emphasis on people and the social fabric, and it confirms that socio-economic sustainability does tend to be prioritized as a concern. Environmental responsibility seems to need special attention if it is not to be lost in the shuffle of other considerations in a Fab Lab.

Perhaps, however, it can be more integral to each Lab's identity. On numerous occasions Karlsen referred to the Lyngen locale as a socio-historical place of importance: the Viking heritage with its special artefacts and significant places, as well as more recent traditions of the region he clearly regarded valuable (Figure 13). These were not to be lost and forgotten; it was also the role (and interest) of the Fab Lab not only to record and document them, but in the case of 'old' technologies, for example, a 200-year-old windmill formerly used to grind flour, to revive and update them, adapting them to today's circumstances. In the case of the windmill, Karlsen was working with a manufacturer on a generator specifically for the ancient windmill design, which could be developed and employed today to generate distributed electricity. From this understanding, to make sustainability concern more visible, local values can be leveraged: values of openness and sharing knowledge, pride in locality and place, respect for all its resources and cultural assets, and an interest in past inventions.

Among European Labs, this connection to the local environment is taken almost to the extreme at the Valldaura Self-Sufficiency Lab in Barcelona (as mentioned in paper 4), where all projects have socio-environmental implications and the Lab's (and building's) cultural history, biotic environment and urban context have blended themselves into the Lab's narrative: how the Lab represents what it is for. The Lab's identity is consistently presented, and its vision enacted in practice visibly and explicitly (Figure 14). It is thereby praised in Fab Lab mythology (Lassiter, 2013), as well as greatly admired by visitors such as the FAB10 delegates.

In the Netherlands, the first thing a visitor to FabLab Amersfoort encounters are the square-metre plant biodiversity experiments in the Lab's outer yard, as part of the organizers' long-running 'Transition Lab' explorations (see also Smith et al., 2015). These mini-plots are so distinctive to the Amersfoort Lab that local commercial products (sold as kits for urban gardening) have been mistaken for the Lab managers' experiments (Figure 15). The Lab is also well known in northern Europe for its self-funded and self-sustaining approach; its commitment to peer production of open source hardware; and its annual FabFuse festival, intended as a low-cost, grassroots and local alternative to the large FABx meeting, with its high participation fees and usually distant venues. These are clear socio-material practices deliberately configured to conform to a particular (environmentally-oriented) vision.

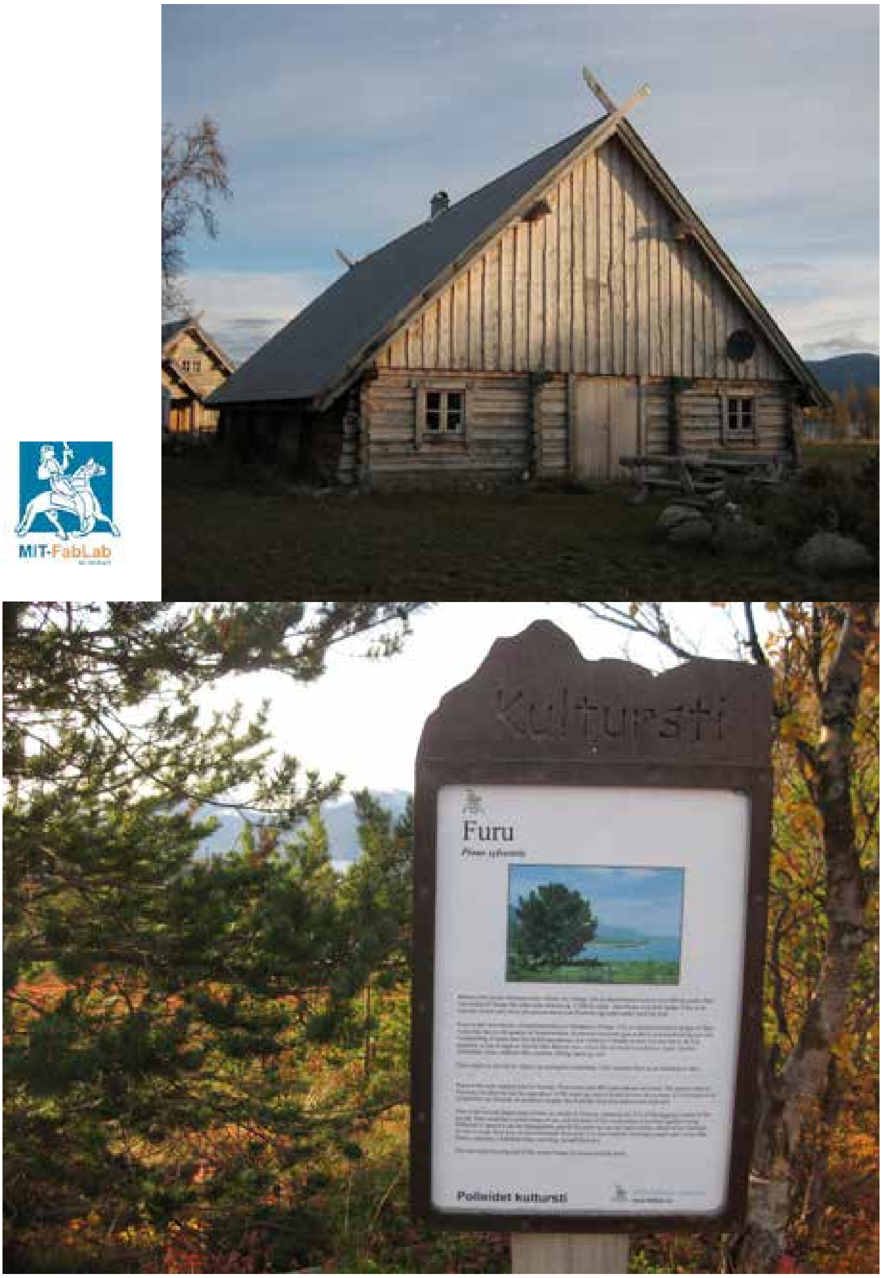


FIGURE 13: MIT-Fablab Norway. Top left: Lab logo. Top right: The Lab building. Bottom: Signpost by MIT-Fablab Norway giving information on the local pine. Other signs give information on archaeological sites and geological features in the area. Source: MIT-Fablab Norway and author.

FIGURE 14: Valldaura Self-Sufficiency Lab, Barcelona.
Top: the Green Fab Lab inside Valldaura. Bottom: gardens and exterior of Valldaura.
Source: author.

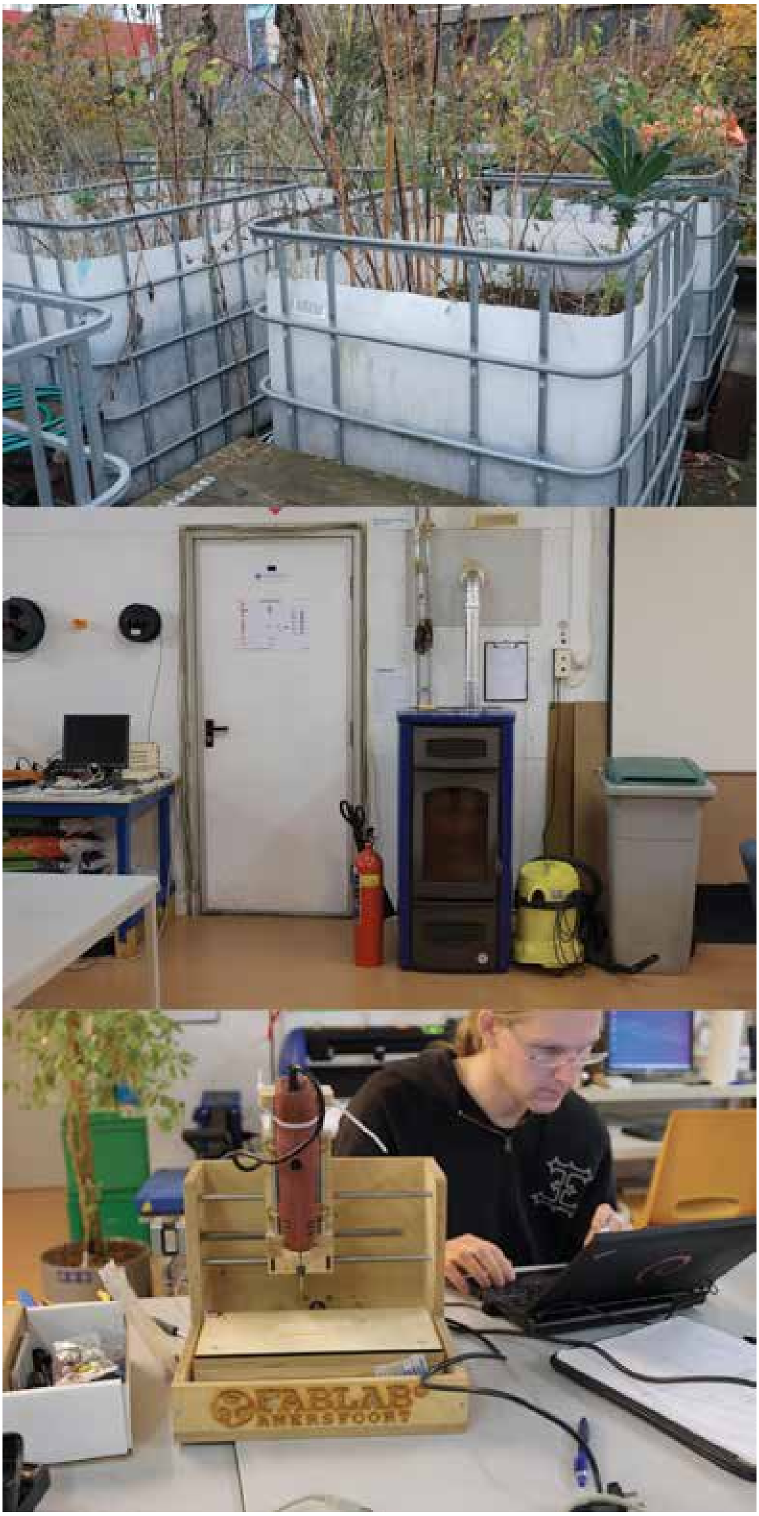


FIGURE 15: FabLab Amersfoort. Top: square-metre ecosystems. Centre: wood pellet space heater. Bottom: open source low-cost milling machine building. Source: author.

The identities of these Labs are thereby carefully and deliberately maintained to accord with socio-environmental principles. Principles manifest in projects and material objects, which communicate messages to outsiders and invite conversations on how they may participate. They are rooted in their geographic locality and history but plans are shareable virtually and adaptable globally. Objects such as an open source milling machine, a plant box, a beehive, a permaculture garden, a wood-pellet heater or a mycelium-brick building experiment, all symbolize access and control: to production technologies for artefacts, food, energy and buildings, and thereby self-sufficiency.

Open access does not necessarily mean low thresholds, however: observers have the agency to decide how they will engage with the project and what they need to learn in order to contribute, while the sociotechnical ensemble of Fab Lab organizers' decisions, users' skills and motivations, and characteristics of the material object, together mediate how peer production will proceed. This will be discussed further in the next section. It is a way of working far from conventional consumption and commodification patterns, and it is therefore a process that must be learned.

5.4 CONTRIBUTION 4: OPPORTUNITIES IN DESIGN AND BY DESIGN

Turning from the Labs discussed in the previous section to the Lab described in paper 4, how was sustainability materialized and what opportunities could be identified for more responsible practices? The fourth contribution of this dissertation has been to articulate how design, specifically the construct of open design, can come to represent a space, a process and a methodology by which the socio-environmental sustainability of material peer production practices can be explored and better understood by a community.

As seen in paper 4, Fab Labs do not appear to be counterspaces that inherently promote environmental sustainability in their core paradigm, in comparison to, for instance, the Alternative Technology movement of the 1970s (Smith, 2005) or personal fabrication activities (as "grassroots innovation") in Latin American countercontexts which can be linked to the Appropriate Technology movement (Smith et al., 2014; see also Sperling et al., 2015). In one direction, as described in chapter 2, framings such as Appropriate Technology help guide strategy and action and then justify it. They can also aim at attracting designers to their cause: designers may be recruited to these types of communities or problems by promoting "Appropriate Design" (Nieusma, 2004).

Alternatively social groups, alternative practices and countercontexts in Nordic countries may recruit Participatory Design (Bjerknes et al., 1983) and commons design principles (Ostrom, 1990) to their purposes, that is, to "open production" (Seravalli, 2014b). Similarly, Critical Making, as previously mentioned, is a tactic employed not in the creation of technology, but rather its examination: a "mode of materially productive engagement" that is both physical and conceptual (Ratto, 2011). It too borrows from or recruits design, that is, Critical Design (Dunne and Raby, 2001) and Adversial Design (DiSalvo, 2012), to draw citizens, including designers, into a more discursive engagement in making and technology (Ratto and Boler, 2014). Fab Labs also appear to be successful in recruiting designers via an Open Design framing (Tooze et al., 2014), but how socio-environmental sustainability figures into this framing seems to need constant negotiation.

The Fab Lab in paper 4 well illustrated how its organizers attempted to use the Lab as an experimental platform for shepherding an open design future. The managers as teachers wished to strengthen design capability for fabbability and personal fabrication: users learning how to design for digital fabrication and for what results technologies were best suited. The relationship between the bit and the atom was thus key to optimum fabbability (Figure 16) – and is central in Fab Lab myth-making (Gershenfeld, 2005).

Learning design for digital fabrication also implicated environmental issues in paper 4. Better designs for, for example, 3D printing could reduce printing time without compromising desired characteristics, and this would carry environmental benefits regarding energy consumption. Better designs for laser cut objects could be more accurate than cut by hand, allowing press-fit and would not require glue or screws. In a sustainable future, moreover, it is envisioned that digital fabrication (particularly additive manufacturing in larger scale production) will have positive environmental benefits, such as lightweighting (Gebler et al., 2014). This may be a future projection, but Fab Labs are the experimental platform of the future being lived today. They can thereby potentially be the key drivers behind an enhanced design literacy for more citizens regarding sustainable 'fabbability' (environmentally, socially and economically). The bit–atom dynamic teaches what can be shared in 'open design', such as success stories and information on sustainable solutions; what can be adapted and customized; what can be designed that has not previously existed, according to need; what can be made more accurately, or more complex; and what can be learned from history.

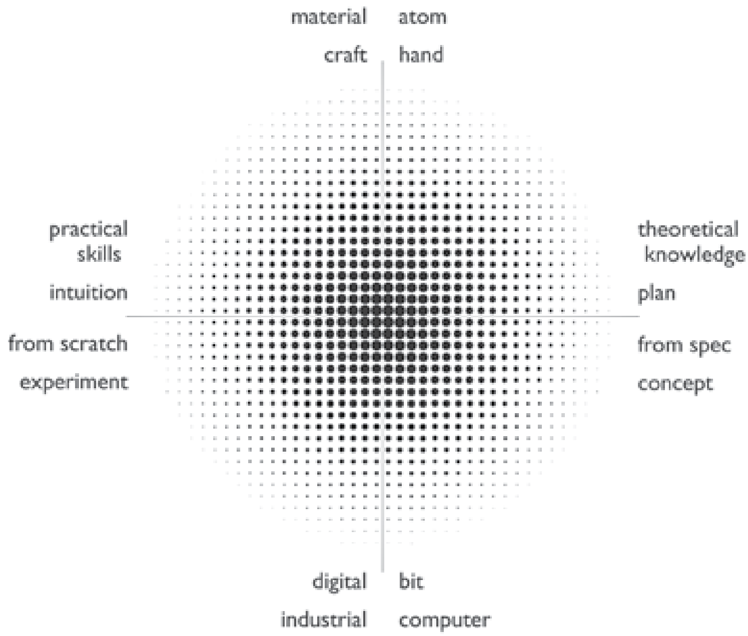


FIGURE 16: The spectrum of Fab Lab elements. A dialogue among all the elements best ensures success and sustainability in Fab Labs and open design processes, allowing strategic thinking as well as ad hoc and contingent responses in the quest to democratize production. Digital-material making involves both experimenting and designing; environmental sustainability is implicated in the need to consider local resources and conditions but also more effective planning for the future. Source: paper 4, Figure 2.

The digital may appear inevitable, but it is qualified by the material. One side of the diagram in Figure 16, top or bottom, does not exist without the other in the Fab Lab social world. The critical discourse claiming that makers too easily ignore material issues, from plastic waste to energy consumption, from long supply chains to local resources, is a valid concern, but equally, it is a concern when certain maker communities (such as the environmentally-oriented makers in paper 2 and the Waste-lab makers in paper 4) refuse to engage with digital fabrication technologies and their potential to improve the environmental footprint of material production.

The diagram therefore illustrates the dialogic elements of design for digital fabrication and individual open design projects and processes, all of which embody environmental issues and provide opportunities for more environmentally conscious practices. The diagram also represents how material peer production works in practice: as *collaborative* open design. In paper 4, the dialogue between the ad hoc and the planned, working "from scratch" and "from spec", referred to the Fab Lab's wish to combine the best of maker culture with the best of design school competence: where the ability to work practically and skilfully with what was to hand would meet the ability to plan conceptually and asynchronously. Open design and material peer production is best accomplished when design concept and modularity (on the right) meets the localized and contingent (on the left) (Troxler, 2013; Kostakis and Papachristou, 2014).[32]

32 See also the WikiHouse Design Principles: www.wikihouse.cc/about/ (accessed 1 September 2015).

This dynamic is also captured in Ratto's (2007) discussion on Free/Libre Open Source software (FLOSS) developers' alternating between "tinkering" and "redesigning" in their work practices. In Ratto's study (2007), the immediacy and contingency of the developers' "tinkering" took place alongside, and could be incomplete without, the more coordinated and formally represented processes of redesigning parts of the software kernel, over longer periods of time. The shifting between these modes necessitated (or signalled) a shifting between what was actually being worked on, how this work was represented and how the actors negotiated the process: who participated and how. Crucially these shifts therefore illustrated how access and participation was mediated in peer production. (Ratto, 2007)

Neither development on the Linux kernel in Ratto's study (2007) nor collaboration on solutions in a Fab Lab could be effected without a pre-emptive commitment to "openness" and knowledge sharing. Not every contribution in peer production is integrated, however; open access does not mean automatic full participation. Peer production is a space that is freely entered, but actors must *enter* the space (Figure 16) to access the shared resources, contribute and participate in production, and learn the communication protocols therein.

Both developers' and makers' tinkering and redesigning processes make explicit the embodied knowledge that is being shared and distributed: ad hoc tinkering being more "doable" (Ratto, 2007) and experiential, one could say localized, and conceptual and planned redesigning being more systems-conscious and future-minded (Ratto, 2007), one could say also replicable. Small tinkering experiments make sense only within the broader frame of the common endeavour. They may otherwise unintentionally marginalize their actors, as was seen with the Waste-lab group in paper 4, who would not engage with digital fabrication nor future-oriented design concepting in their explorations. Fab Labs who do not enact strategy will find it challenging to sustain themselves and remain relevant to their communities of users. Likewise, designing and redesigning is better ensured success with tinkering and small, experimental prototyping actions based on existing resources, else they run the risk of overextending themselves and/or proposing entirely inappropriate, locally irrelevant solutions.

Again, a sole focus on one side of the diagram, left or right, is not sustaining in the Fab Lab social world, for individual projects nor for the going concern of the Lab itself. Through promoting 'open design', the Fab Lab in paper 4 aimed to guide their users to better understand where resource (material, time, skill) limits lie; what is locally 'appropriate', suitable and fitting; and what lessons can be learned from experimentation. Exploring the tinkering–designing/bit–atom interconnection in the Fab Lab allowed users and organizers to understand the relationship between the ideal and the realizable, whether what was to be realized was a currently relevant, practical project or the 'revolution': configuring aspects of the open, distributed, democratized production paradigm.

Fab Labs thereby have great potential to distribute the *literacy* of sustainability by design, as mentioned above, but also to distribute the *benefits* of design, by promoting design *by* society (Woodhouse and Patton, 2004). Some of the opportunities to promote 'a more sustainable Fab Lab', however, on the ground and in everyday practice, differ from Lab to Lab. (And 'appropriate' and 'responsible' may indeed be better evaluative terms than 'sustainable'.) This could make sustainability in Fab Labs akin to a "fire object" (Law and Singleton, 2005), meaning that the very meaning of sustainability in each Fab Lab shape-shifts and is markedly dependent on things that are absent: a network absented in its virtuality, an invention absented in the past, an electronics factory absented by geography, or a sense of responsibility absented by the identity as an alternative third space. Or rather: the 'fire' is the *immaterial* vision around which social groups collaborate and innovate (as in the FLOSS project described in Darking and Whitley, 2007), the *imaginaire*, which may feed *or* eclipse the material work that constitutes the work practice – and their very material configurations that extend outside the social world such as mining practices or toxic fumes.[33] Fab Labs appear to need help to deal with these very real, but easily hidden, material issues, and ecology-oriented maker communities need to engage with these issues.

33 As metaphors, fire and fluid are not without their problems and have been evoked as an entry point for thinking about the configurational aspects of Fab Labs and not as an analytical tool per se.

This chapter has summarized the cross-cutting contributions of the dissertation. It has illustrated how Fab Labs, as sociotechnical configurations, form ideologies, which become enacted through interaction and embodied in materials and objects. The total of the practice-bound *imaginaire* (Hyysalo, 2006; 2010) of the Fab Lab social world promotes revolution in its discourse (Strauss, 1978): creating a more empowering, socio-environmentally beneficial world for more people, by democratizing production in peer-to-peer processes. The strength, the *aura*, of the *imaginaire* motivates and organizes practice (Hyysalo, 2010; Flichy, 2007), but the chapter and the papers in the dissertation have illustrated how this social world also comes into conflict with other social worlds, such as incumbent institutions. *Imaginaires* are "riddled with contradictions" (Flichy, 2007, 209), and the dynamics of contradiction and conflict serve to render certain issues invisible. As Labs struggle in their role as countercontext (Pfaffenberger, 1992), struggle to enact ideology and struggle to simply make financial ends meet, compromises can configure themselves as sustained breaches of Labs' own visions. Moreover, among the invisible issues are often the environmental issues associated with mass production, issues that would be mitigated if explicit engagement and an explicit dialogue on how to move towards a democratized, distributed production paradigm were addressed more consistently in individual Labs and in the Fab Lab network. Nonetheless, there are several exemplary Labs and certain practices seen as "desirable", "relevant" and "realizable" (Hyysalo, 2010, 76) in some Labs that clearly carry socio-environmental benefits. Concomitantly they promote the *imaginaire* of production revolution, which is grassroots, peer-to-peer and open, digital-material, experimental and tinkering – but also strategic and designed.

A young visitor at the Espoo Mini Maker Faire dismantles a phone during a Fairphone Urban Mining workshop, Finland, October 2015. Source: author.

6

FINAL IMPLICATIONS AND CONCLUSIONS

The previous chapter has shown how discourse on democratizing production is enacted in Fab Labs, especially via material artefacts. If Fab Labs are to offer a meaningful step away from the negative environmental impacts embedded in mass production, there are practical obstacles that they, and any organization, face with regard to time constraints and entropic routines. Nevertheless, given the strength of the Fab Lab ideology, the Fab Academy and the network itself, Fab Labs are (arguably) the best actor in the maker movement to communicate its impacts; generate new knowledge, practices and solutions; and ensure making has meaning. Achieving this requires reflection and critical discussion: do everyday actions reflect vision, values and ideology? Environmental sustainability is but one thread in the sociotechnical fabric of Fab Labs, but it is an integral thread. The dissertation has demonstrated, through examples from everyday events observed and heard in Labs, that environmental issues embed themselves within other issues in the Lab and ideology is not so easily enacted.

The contingencies, the very situatedness of Fab Labs, mean that every Lab must be built anew. Even experienced Fab Lab founders and managers, the "gurus", as they are known in the network and the Fab Academy, must take time to understand the local conditions when setting up a new Lab to stimulate and sustain engagement with the local user and stakeholder communities – to understand the local needs. There are therefore relatively few default modes of operation or established routines, no Lab-in-a-kit, that can be implemented quickly, allowing more time and focus on identifying strategy and target users nor the most appropriate action plans or partners. The mundane, setting up the Lab and its procedures, maintaining it, maintaining inventory, serving users and organizing short-term activities, easily takes precedence; the *what* of what needs to be done can dominate the *how* things could or should be done, and especially *why*.

The Lab's situatedness is therefore its strength, the source of its identity and mission, which can help sustain it over time and nurture commitment. It is also its weakness, as this identity and mission must be co-constructed among a variety of actors, and usually repeatedly. If not, the *why* of the Fab Lab dissolves, Labs discover after a certain period of time that they have become just another printing service (or even a place of no digital fabrication whatsoever), and they need to firmly establish a new strategic direction and a clearer identity of what they are for (as seen in paper 4 and as reported by several Labs in interviews and in the FABx meetings).

There are several messages in this dissertation that Fab Labs can take away. The aim is not to predict the future trajectory of Labs or the network, but to highlight critical points of divergence and tension. Both the literature review in paper 1 and the discussion of the universe of discourses in paper 4 questioned if distributed production and the maker movement will contribute to consumerism and overconsumption, rather than to serve to abate it. In paper 4, commodification and commercialization were alternatively seen as economic benefits for micro-entrepreneurs or as threats to the original ideology of making as a counter to consumerism. For Fab Labs this translates into a question of not mere empowerment, but *how* it should be effected (and, of course, *who* should be empowered, but that is an ongoing and salient question). Making things easier for new makers (via kits, for instance, or easier user interfaces for software) also tends to remove functions and control from the hands of the very users intended to be empowered. In fact, given there is much talk on the need for manuals and guidelines for people who want to set up Fab Labs, this threat also exists here. Such a manual can pre-empt and make invisible the very questions a Fab Lab founder should ask him- or herself: what is this Fab Lab for? Fab Labs and the network will develop and mature, consolidate and become infrastructure in some ways beyond the existing state of "ad hoc ashrams" (Hunting, 2009; see pp. 33–34), but the direction of decentralizing and distributing control to regional bodies and keeping the remit of Fab Labs open to ensure diversity still appears preferable to an easily implementable, standardized Lab-in-a-kit. This would also ensure the new, young Lab understands its role and responsibility (and the sustainability implications entwined) in its situated local community. In addition, such open structures need not prevent the development of environmental and safety guidelines that could be developed for Fab Labs, as recommended in paper 2. As de Laet and Mol (2000, 250) highlighted, "Sometimes abandoning control may contribute to spreading what one has been making."

For Fab Labs there is also a need to engender a balance between becoming normalized and institutionalized (thereby better ensuring acceptance in the local community and – most importantly – funding) and maintaining an open and fluid identity committed to espoused ideology: the democratization of technologies and offering an alternative to passive consumerism. Open access *is* crucial, it appears central to the relative diversity of users that does exist (according to interviewees and my observations), and it forms the core of the learning and discovery processes that unfold in Fab Labs. Fab Labs' rich diversity is their asset, just as the heterogeneity and ambiguity of the internet, the vast diversity of interests, is its core strength (Flichy, 2007, 204-205).

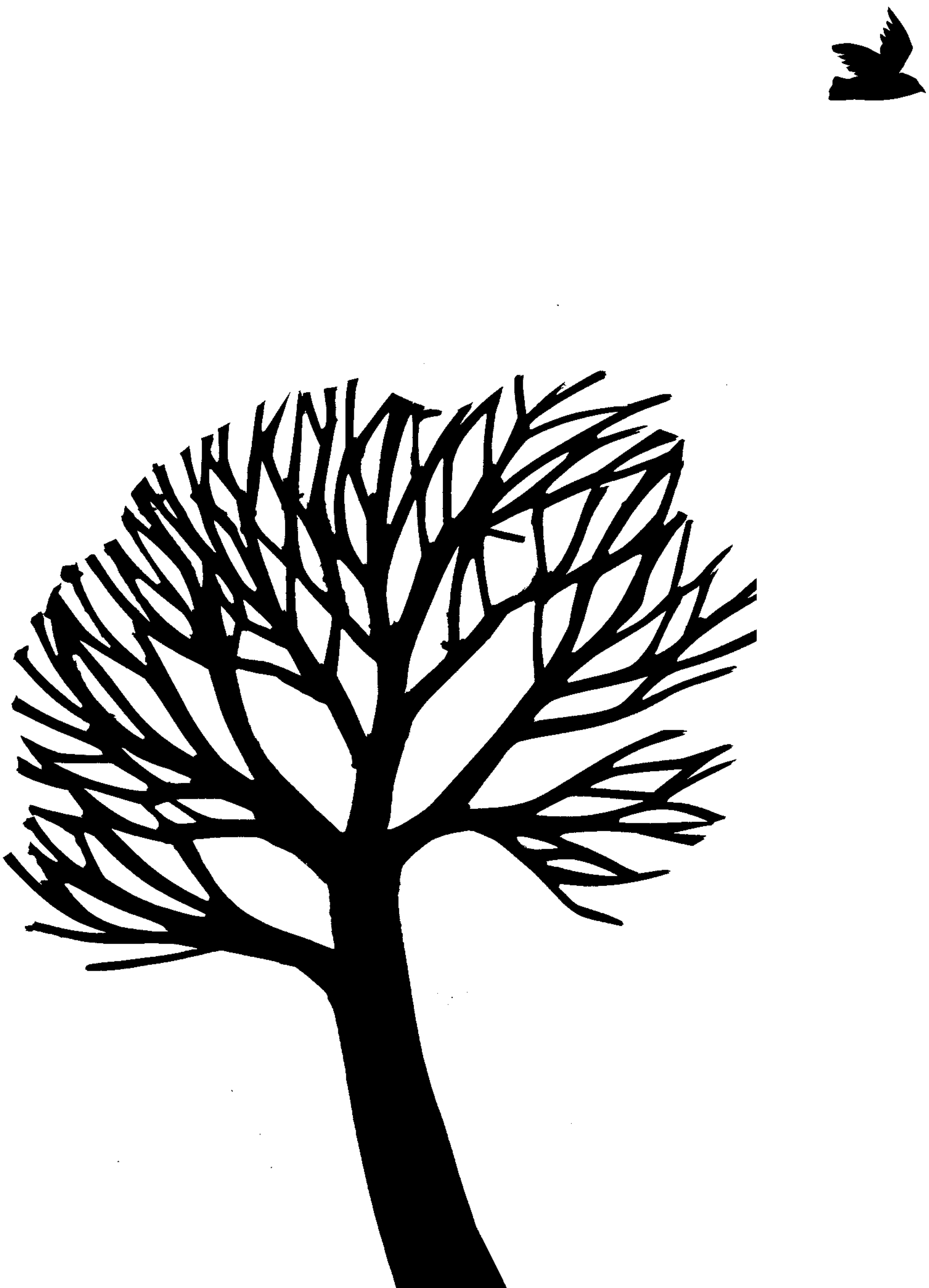
With regard to potential Fab Lab 'projects', emerging evidence suggests that citizen engagement in, for instance, environmental technologies can help in their diffusion and adaptability (Rohracher, 2003; Hyysalo et al., 2013). Despite this potential, thus far it appears Fab Labs, hackerspaces and makerspaces have been largely overlooked by policymakers as potential "innovation intermediaries" (Stewart and Hyysalo, 2008), particularly for sustainability-directed solutions, inventions and related practices. Based on the findings in this dissertation, the configuring, facilitating and brokering of new technologies (Stewart and Hyysalo, 2008) in Fab Labs is not always as "democratic" as espoused, nor oriented to future visions characterized by sustainability. Only few Fab Labs are consciously choosing projects led by sustainability issues or discussing their values in relation to undesired 'consumerism'. Fab Labs may need outside help, in environmental assessment, in selecting projects and to enliven the critical debate. As Russell and Williams (2002, 49, my emphasis) have stressed, "The emergent and unpredictable nature of sociotechnical transformations points again to the value of flexibility and constant monitoring, maintaining channels of communication and *arenas of debate*, and avoiding disincentives to *open appraisal*."

When actors in these sociotechnical dramas fail to pay attention to politics, or keep their activities out of the realm of public debate, there is the danger that discourse and vision become "an empty, hollow signifier" (March and Ribera-Fumaz, 2014), that communities fail to form or fail to sustain, or that they inflict damage on the very citizens they intended to benefit, by avoiding discussion on the wider consequences of their actions (Flichy, 2007; Turner, 2006). Should they succeed, on the other hand, they may prove to be the gateway to greater citizen participation in material production and society-making: encouraging self-discovery and collaborative peer learning, and making 'making' – of all kinds – socially acceptable at the very grassroots (Wüstenhagen et al., 2007). Indeed, Morelli (2003) has suggested that designers may have the ethical responsibility to assist people to design their own conditions of wellbeing, and material peer production is one route to this goal.

Alongside providing deep and detailed knowledge on particular Fab Labs, representative and emblematic, and presenting implications for the network and the maker movement, the dissertation has richly illustrated how ideology unfolds and *imaginaires* shape and are shaped, remaining open and incomplete, in everyday practices in peer-to-peer counter-communities. These processes are especially evident in material assemblages, which embody both rhetoric and routine. This research contribution complements other research on "material participation" (Marres, 2012), but does so by examining how socio-environmental sustainability is represented in deliberate *counter*-spaces, physically and ideologically set apart from the mainstream – rather than how the public currently engages materially with environmental issues in the realms of politics and everyday practices. In future research, there is value in both foci and a need for still more empirical research, to better understand how the present and the mainstream meets the emergent and the niche in future production patterns.

The focus on countercontexts in this dissertation has thereby demonstrated how peer-to-peer material production is orchestrated and improvised in practice, as projects, as communities and as the intermediating spaces of Fab Labs. Such processes have been presented in this work as successes or failures, due to the dynamics and conflicts among factors, the experimental and the designed, the local and virtual or global, and the immediate and the ideal. Further research on longitudinal peer production projects is recommended, to contribute valuable knowledge on how the assemblages of materials, people, spaces and interactions mediate access and participation. Particularly when the sites of research involve emerging technologies and have clear sustainability and environmental implications, as in this dissertation, such studies can tell us more about citizens' changing roles in production and the effects and potentials of a rapidly digitalizing society.

From this standpoint, my intent with this dissertation sympathizes with Benkler and Nissenbaum (2006, 417)'s position: "Unlike many political analyses of technologies, however, ours does not warn of a direct threat of harm. Rather, it warns of a threat of omission. We might miss the chance to benefit from a distinctive socio-technical system that promotes not only cultural and intellectual production but constitutes a venue for human character development." If the clear environmental issues are also taken into explicit consideration, in ways alluded to in this dissertation, Fab Labs offer a promising platform for new prosumption patterns.



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Original Research Papers

Paper 1.
Kohtala, C., 2015. Addressing sustainability in research on distributed production: an integrated literature review. Journal of Cleaner Production 106, 654-668. doi:10.1016/j.jclepro.2014.09.039
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Paper 2.
Kohtala, C., Hyysalo, S., 2015. Anticipated environmental sustainability of personal fabrication. Journal of Cleaner Production 99, 333–344. doi:10.1016/j.jclepro.2015.02.093
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Paper 3.
Kohtala, C., Bosqué, C., 2014. The Story of MIT-Fablab Norway: Community Embedding of Peer Production. Journal of Peer Production 5. http://peerproduction.net/issues/issue-5-shared-machine-shops/peer-reviewed-articles/the-story-of-mit-fablab-norway-community-embedding-of-peer-production/
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Paper 4.
Kohtala, C. Making 'Making' Critical: How Sustainability is Constituted in Fab Lab Ideology. Unpublished, in review.

Paper 1

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Review

Addressing sustainability in research on distributed production: an integrated literature review

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ABSTRACT

This paper presents an integrated literature review on how the environmental sustainability of distributed production is studied in a variety of disciplinary sources. The notion of distributed production suggests an alternative to mass production that differs in scale, location and consumer–producer relationship. Understanding its environmental implications (and thereby dematerialization potential) is regarded pertinent and timely. Key themes in the review included how distributed production can promote product longevity and closed material loops, as well as localizing production. New and closer ties between producer and consumer seemed central discussions but were underdeveloped with regard to sustainability potential. Empirical work was seen especially in research on Additive Manufacturing Processes, while the bulk of the studies were conceptual explorations with little testing in the real world as yet. This affirms the emerging nature of the topic and points to a clear need for more (and more diverse) empirical research. The review summarizes the opportunities for greater environmental sustainability as well as potential threats that could serve to guide and improve these novel practices today. It sets the stage for 'distributed production' to be examined as its own phenomenon by proposing how it can be characterized and suggests that a research agenda could build upon the work initiated here.

1. Introduction

The notion of *distributed production* conceptualizes a shift in consumption and production patterns away from conventional mass production, with its long, linear supply chains, economies of scale and centralizing tendencies. The boundary between consumers' and producers' roles blurs and the intermediaries between them disappear or transform. Drivers for such reconfigurations include benefits for producers in terms of cost or competitiveness (Jiang et al., 2006; Piller et al., 2004). Distributed production thus includes a range of current and emerging practices where private citizens have increased capacity to affect what is produced, from product personalization to personal fabrication.

Such an alternative structure, even paradigm, should also have the potential to be leaner and cleaner, mitigating or eliminating the social and environmental problems associated with mass production. This raises the question of what knowledge currently exists on the sustainability of distributed production and how the research community is approaching the acquisition (and implementation) of such knowledge.

This paper presents an integrated literature review that examines what aspects of distributed production researchers are studying when they aim to establish links to sustainability beyond simply economic sustainability. As there is not yet a clear, agreed understanding of "distributed production" as such, the review targeted several research fields studying decentralized, networked alternatives to mass production.

Practices that integrate production and consumption are not new, but today they are especially enabled by (and thereby defined by) advances in digital manufacturing technologies and the internet (Kumar, 2007; Marsh, 2012). These activities are now evolving and entering the mainstream, from customization and

Abbreviations: 3DP, 3D-Printing; AM, Additive Manufacturing; DIY, Do It Yourself; EIA, Environmental Impact Assessment; EOL, End of Life; IE, Industrial Ecology; IM, Injection Moulding; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; MC, Mass Customization; MCP, Mass Customization and Personalization; MP, Mass Production; OSAT, Open Source Appropriate Technology; PSS, Product-Service System; RM, Rapid Manufacturing; RP, Rapid Prototyping; RT, Rapid Tooling; SLS, Selective Laser Sintering.

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personalization to co-production or personal fabrication of goods. Whether such a shift in production mode can help dematerialize current consumption is uncertain; it can thus be argued that the sustainability assessment of these practices is best done sooner than later.

2. Theory and background

In engineering and operations management, distributed production is often a synonym for distributed manufacturing (Windt, 2014) and takes the perspective of production planning for networked or "virtual" enterprises aiming for flexibility, agility and greater customer orientation in manufacturing and mass customization (Bruccoleri et al., 2005; Leitão, 2009; Tuma, 1998). Agility is a key characteristic, as the term *distributed* has its roots in computing and communications, when a more robust network that distributed nodes rather than centralizing or decentralizing hubs or switches was developed (Baran, 1964; Windt, 2014).

It is also a term used more widely ideologically as well as epistemologically, when discussing alternative business models and opportunities for more socially beneficial and responsive production and consumption. The notion of "distributed economies" promotes small-scale, flexible networks of local socio-economic actors using local resources according to local needs, in the spirit of sustainable development (Johansson et al., 2005).

The blurring between production and consumption, another key characteristic of distributed production, may instead be referred to as "prosumption" and the consumer a "prosumer" (Toffler, 1980), for whom production becomes part of the consumption process. When prosumption involves peer-to-peer networks, some researchers refer to the practice as "commons-based peer production" (Benkler, 2006). Prosumption and peer production have been examined from the perspectives of, for instance, markets (Xie et al., 2008), behavioural science (Ritzer et al., 2012), consumer research (Ritzer and Jurgenson, 2010) and Marxist critique (Moore and Karatzogianni, 2009). This research has especially focused on digital artefacts and internet-based initiatives, but distributed peer production of tangible products is attracting increasing interest in research and practice.

In the current study, material, physical goods as the output of distributed production call particular attention to appropriate, responsible and equitable use of materials and energy. Moreover, the most novel activities relevant in this study are for some the most intellectually compelling and for others potentially the most disruptive: that is, "personal manufacturing" (Bauwens et al., 2012), "personal fabrication" or "fabbing" (Gershenfeld, 2005), "commons-based peer production of physical goods" (Troxler, 2013) or simply "making" (Anderson, 2012; Gauntlett, 2013; Hatch, 2013). For these reasons this literature review has selected the lens of distributed production's *environmental* sustainability, not to the exclusion of the social and economic dimensions but rather foregrounding the environmental issues.

As mentioned, research in this area does not yet have a common understanding of the phenomenon (or phenomena), and terminology, success factors, indicators, system boundaries and units of analysis vary from field to field. A survey that aims to map the topic of distributed production is therefore deemed valuable, especially in view of its potential as a new and more sustainable paradigm. This enables a better understanding of how researchers regard distributed material production in relation to a more sustainable present or future, how environmental sustainability principles are operationalized or theorized, and what methods and data are seen as tools to study the phenomenon.

The literature review described in this paper undertook to examine three research questions:

- what fields, disciplines or specialists are discussing distributed production and how they are addressing it;
- how sustainability is represented and the nature of the relationship between environmental sustainability and distributed production; and
- what research gaps currently exist as well as what research directions are most promising.

The results reveal the current research landscape, the main topics of concern and point to opportunities for further research as well as improved practices. The methods by which the review was conducted are described in the following section.

3. Methods

The choice of an integrated literature review refers to a review that describes and synthesizes the knowledge from diverse sources (Whittemore and Knafl, 2005). It is especially appropriate for new subjects where incorporating several theoretical domains is seen as a strategy to developing new conceptual models, research agendas and/or metatheories (Torraco, 2005). This is in contrast to systematic literature reviews which generally aim for a complete compendium of the literature, especially in a mature topic and often from the perspective of one knowledge domain. In the latter the search for peer-reviewed journal articles is therefore often done via databases.

In this study an integrated review allowed for more considered selection and inclusion of varied data sources, theoretical as well as empirical, and emphasis on portraying a complex concept through a diverse and broad sampling frame (Whittemore and Knafl, 2005). The objective was to target representative (rather than comprehensive) channels of research, including both journals and conferences, that reached the most relevant audiences and would have high potential in the researcher's estimation to examine aspects of distributed production and its environmental sustainability.

The study therefore first identified the target sources as well as the target keywords. The journals were selected according to field and impact factor, the conferences according to the field(s) represented and the conference organizers' intention to combine research and practice (bridging academia and commerce). This approach allowed one researcher to better tackle the screening process and ensure rigour in the literature search stage, especially considering the challenging lack of consensus on terminology.

The diagram in Fig. 1 depicts the target journals' scientific areas, indicating how they were selected to represent as wide a spectrum as possible (while acknowledging that journals and their individual published studies may be cross-disciplinary). The scientific areas are based on a mapping of scientific communications as described in Rosvall and Bergstrom (2011). No journal from the Life Sciences was examined, as any relevant theories or knowledge (on e.g. consumer psychology) are likely to be incorporated into other studies, as is the case in some design or consumer research, for instance. Design, production, consumption and environmental studies were regarded as relevant starting points. The full list of journals and conferences selected is found in Appendices A and B.

The topical scope of the literature search is depicted in Fig. 2. The target was a spectrum of distributed prosumption activities as the focus of research, where the consumer (customer, user, prosumer or 'maker') is able to intervene in design and production to a greater extent than in mass production, resulting in a tangible artefact. This increased agency, integration or input ranges from personalized options in a mass customizing or distributed manufacturing service to fabbing: machine-aided self-fabrication of one's own design, e.g. in a Fab Lab (a space equipped with small-scale digital manufacturing equipment the individual operates herself) (Gershenfeld, 2005).

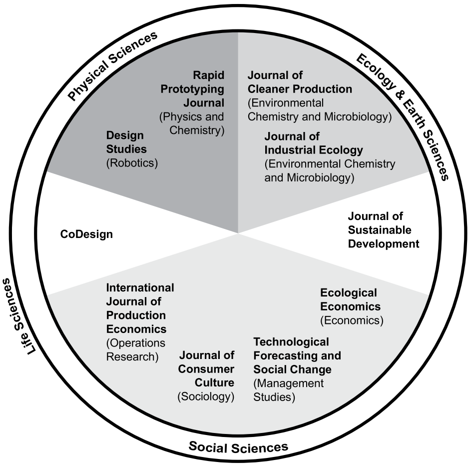

Fig. 1. The journals targeted in this review and their scientific research fields. (Eigenfactor categories are given in brackets.)

Regarding sustainability, it was hypothesized that research on these activities would address various environmental aspects. Study topics and their objectives may include less impactful supply chains (see e.g. Huang et al., 2013), cleaner manufacturing processes (e.g. ATKINS Project, 2007) and/or overall less material flow.

The relevant keywords for the review therefore included *distributed production*, *distributed manufacturing*, *mass customization*, *personalization*, *peer production*, *prosumption*, *fabbing*, *personal fabrication* and *Fab Labs*, but the selection process was not restricted to these keywords, given the wide range of terminology actively used. Instead the titles, abstracts and keywords of all full papers (and full paper itself where necessary) were examined for relevance to the *topics* (i.e. synonyms and comparable constructs, not simply keywords). The procedure aimed to capture activities and operations as well as technologies (i.e. digital fabrication, especially *additive manufacturing*). With regard to environmentally relevant issues, the assumption was that 'sustainability' must be important enough that it was directly addressed in the title or abstract (by the words *sustainability*, *environment* or *green*) and not hidden within the contents of the paper. The timeframe for the literature collection was the decade from 2002 to 2012, as before this time there was little or no interface between these technologies and services and private citizens.

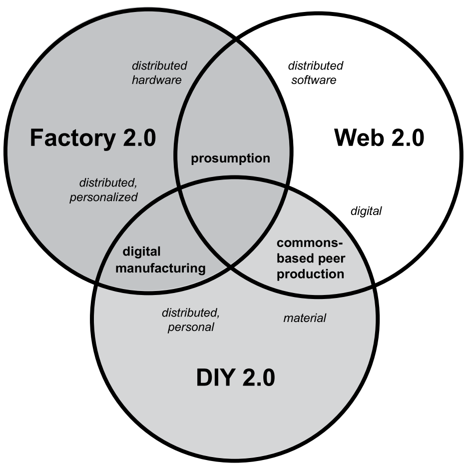

Fig. 2. The contents scope of this literature review (in grey). The review focused on material products and excluded digital artefacts (as produced in 'Web 2.0'). It took into account digital manufacturing capabilities in production: in distributed 'Factory 2.0' activities (thereby excluding traditional mass manufacturing) and digitally enabled, personal 'Do-It-Yourself 2.0' production (thereby excluding conventional handicraft).

The screening excluded editorials, commentaries, book reviews and special issue introductions. Many studies on peer production or prosumption unsurprisingly focused on digital artefacts (such as Wikipedia) or services such as health or tourism, which were excluded. Despite their prevalence in additive manufacturing, studies relating to biomedical applications, automobiles and aerospace were excluded, as being too far removed from the realm of consumer input (i.e. prosumption). Finally, papers related to food were deemed out of scope and those relating to housing and construction out of scale for this review.

To ensure that all relevant papers had been identified, a keyword search using each journal's search function was conducted at the end of the literature search stage. The keywords used were the same used to scan the contents of titles and abstracts as described above (the words in italics and their variants). Moreover, these keywords were entered into the EBSCO Academic Search Elite database and the results screened for relevance. Finally, the reference lists of the relevant papers were examined. These procedures did not yield any new critical sources, especially not the new subject perspectives sought (such as economics or marketing studies). The most *representative* coverage possible was considered accomplished, yielding a total of 29 papers.

In analysis, a table (or concept matrix) (Webster and Watson, 2002) served to list the key themes and summaries for each paper in a qualitative and descriptive format, based on the research questions. The objective was to clarify what aspects of distributed production researchers are studying and how they proceed to examine it, as well as what seems to be *known* about the topic. The table was divided into two parts. Besides general categories such as intended audience, type of paper, method, focus and unit of analysis, and nature of the empirics, the first part of the table summarized how each paper represented distributed production; the user and the relationship between user/consumer and producer; sustainability; and the relationship between the production mode and sustainability.

The second part of the table listed themes that arose from the papers themselves inductively: the authors' own concerns, stated implications and suggestions for future research. It also listed the researcher's own notions on implications and research gaps not discussed by the authors, as well as remarks on, for example, the quality of the paper[1] and the most salient links to other papers in the review. Finally, three to four keywords were ascribed to each paper independent of its own keywords.

This tabulation resulted in (a) a taxonomy or categorical grouping of the papers according to main study focus and audience or research area, as described in Section 4.2, and (b) a collection of the most salient themes amongst the authors, as described in Section 4.3. A content map (as described in Hart, 1998) was then constructed with two aims: in synthesis, to better depict the relationships among the 29 studies, and to illustrate the current

[1] While the perceived validity of the papers had not been a screening factor (non-peer-reviewed conference full papers were included), this was accounted for and studies of deemed lower quality were taken less into consideration in the analysis (Whittemore and Knafl, 2005).

'landscape' of distributed production as both a phenomenon and research subject (Fig. 4). A second map outlined the environmental sustainability issues as discussed by the authors (Fig. 5). These content maps are described in Section 4.4. Sections 5 and 6 then discuss the review's main contributions and implications.

4. Results

The group of 29 reviewed papers is listed in Table 1. The papers are accorded an identifier consisting of a number and its source in an abbreviation which will be used throughout this review.

4.1. General summary of results

All authors of the reviewed papers were based in universities and research institutes, from Europe, the Americas (the US, Canada and Brazil) and the Pacific region (Japan, Malaysia and New Zealand). The vast majority of authors were based in Europe (especially Germany, the UK and Italy).

By far the majority of authors and their intended audiences represented fields that could be described as operations and production management, environmental management and/or design and engineering. Several design studies incorporated sociological perspectives on consumption and identity. Two papers aimed to also reach a policy or regional development audience and one addressed international development. About half (15/29) of the papers were from the Mass Customization, Personalization and Co-creation (MCPC) conferences; five of these were linked to projects and reported on interim results. Many seemed to be initial reports of studies that would later be turned into journal papers or theoretical explorations serving as a platform for later empirical study. Several authors would indeed later appear as contributors to book chapters, notably in Piller and Tseng (2009) and Poler et al. (2012).

Three points may be distinguished regarding this collection of studies. First, it is important to note that no authors used the term "distributed production" as such, with the exception of Manzini (2009) [15-DS] (who referred to "distributed systems"), even as all recognized differences from mass production in their focus area regarding production locations, facility and/or batch sizes, the role and integration of the consumer, and/or the configuration of the supply chain. Preferred terms were mass customization, customization or personalization in the majority of cases (and even art customization in one paper); prosumer in several papers and prosumption as the main term in one study; and fabbing as the main term in one paper.

The second factor of note is the exploratory and propositional nature of many papers.[2] There were relatively few empirical studies and dominant was a sense of model-building and sense-making in order to better inform operational practice. In these conceptual explorations, there was little or no real-world testing reported; existing literature or secondary data from other studies often served as data sources. Where primary data was gathered, it was in the form of lab experiment results (quantitative)[3]; "action research" results[4]; surveys (qualitative and quantitative), interviews (qualitative) and a Delphi study (qualitative and quantitative)[5]; and design experiments and other descriptive material resulting in case-study-type accounts.[6] The tendency to present frameworks and propositions without explaining the observations or experiences that led to them is partly due to the large number of conference papers represented, but it is also likely due to the novelty of the topic.

Related to this novelty is the third factor of note, the scant number of papers that actually address distributed production *and* sustainability. To illustrate this ratio, the number of relevant reviewed papers was compared to the total number of published papers in each journal. The number of relevant conference papers, presentations and session topics that addressed sustainability as compared to the total number was also noted and tallied. These figures are listed in Appendices A and B.

4.2. Topical categories of the reviewed papers

This section describes the results of the first analysis and grouping stage. The three main categories will be discussed in order of their granularity, the first category of studies addressing the process- and technique-specifics of more environmentally friendly practices in additive manufacturing, geared especially to production engineers. The second category of studies, the largest group, addressed production planning and evaluation in mass customization processes, aimed especially at engineers and designers of both products and systems. The third category was more future-oriented and transdisciplinary, studies examining personal fabrication (fabbing) and peer-to-peer production, aimed at various audiences(See Fig. 3).

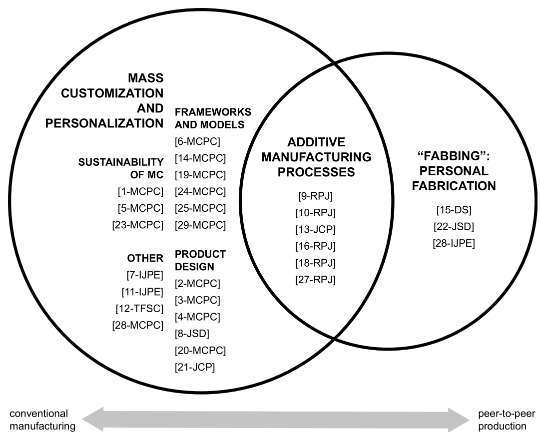

Fig. 3. Categorization of papers and their research topics. The Mass Customization and Personalization category (on the left, with sub-categories) represented activities that are nearer conventional manufacturing than peer-to-peer production. The smallest group was the 'Fabbing' category describing personal fabrication and peer production activities (on the right). Bridging these two categories are the technologies themselves, with a distinct category of papers studying Additive Manufacturing Processes (in the middle).

4.2.1. Additive Manufacturing Processes

Six papers in this review approached sustainability in distributed production by drawing attention to processes or materials in additive manufacturing (AM) or rapid prototyping (RP) (Table 2). The context of this research was mainly industrial scale and the AM systems discussed in these papers mainly for prototype or component fabrication. These studies were nevertheless included in this review as AM technologies are increasingly relevant to mass customization (the MCPC conferences have sessions devoted to AM) as well as services or facilities offered in peer production (fabbing).

[2] i.e. papers 1, 2, 5, 6, 8, 14, 15, 17, 19, 22–25, 29.
[3] Papers 9, 13, 16, 18, 27.
[4] Paper 12.
[5] Papers 7, 20, 21, 28.
[6] Papers 3, 4, 26.

Franco et al. (2010) [13-JCP], Mognol et al. (2006) [18-RPJ] and Telenko and Seepersad (2012) [27-RPJ] focused on electricity consumption and energy efficiency; Dotchev and Yusoff (2009) [9-RPJ] and Marchelli et al. (2011) [16-RPJ] on material recycling and optimization; and Drizo and Pegna (2006) [10-RPJ] on environmental impacts more generally in a review article. These articles were published in the Journal of Cleaner Production and Rapid Prototyping Journal and claim these audiences accordingly: production engineers aiming for cleaner processes in RP or rapid manufacturing (RM).

Nearly all authors lamented the lack of research in this area: studies that would validate the claim that AM technologies are more environmentally benign than conventional manufacturing methods in terms of waste, energy, material use, emissions and so on. The study described in [27-RPJ] directly compared AM with mass production (MP) by determining the 'crossover' production volume at which it makes environmental sense to produce a part using selective laser sintering (SLS) rather than conventional injection moulding (IM): SLS was more energy efficient only with very small production volumes. However, as SLS also allows small batches at the same cost per piece and customization of each piece or batch to an extent that IM can never reach, one conundrum in researching the sustainability benefits of distributed production becomes apparent: the trade-off between high environmental impact per unit in small volumes and low impacts per unit but in mass quantities. This also entails the challenge to identify the most sensible comparison point and system boundaries. (Chin and Smithwick (2010) [5-MCPC] also attempt a comparison between mass customization and mass production using secondary data, discussed in Section 4.2.2.1.)

Three lab experiments highlighted how environmentally-oriented production planning is often concomitant with financial savings in electricity (i.e. [18-RPJ] and [13-JCP]) or material use (i.e. [9-RPJ]). A further study, [16-RPJ], experimented with recycled glass powder as a new material in 3D-Printing (3DP) technology.

The final paper in this category, [10-RPJ], was a review article on environmental issues and evaluation in AM. The authors focused particularly on health and safety, waste and energy, highlighting the health and environmental risks due to material toxicity that have not yet been identified (even at the time of writing this review, as confirmed in Huang et al., 2013). Aside from toxicity during use, the authors pointed to the disposal and post-processing stages as problematic because of the materials' unknown properties.

4.2.2. Mass Customization and Personalization

The second major category, Mass Customization and Personalization, is the largest. It has been divided into four sub-categories according to topic, audience and knowledge-building aim as regards sustainability (Table 3).

4.2.2.1. Sustainability of mass customization. Three papers discussed how to evaluate the sustainability of mass customization versus mass production by breaking down their stages. Chin and Smithwick (2010) [5-MCPC] and Petersen et al. (2011) [23-MCPC] both attempted to identify which MC stages are clearly more environmentally benign (or hold potential to be). Badurdeen et al. (2010) [1-MCPC] focused on the post-use stage, which they regarded as under-addressed, in a conceptual exploration on closing MC resource loops.

4.2.2.2. Frameworks and models. A sizable proportion of the papers reviewed put forth frameworks and tools for rethinking the mass customized offering, evaluating and improving its environmental footprint, and better understanding how to leverage MC characteristics to combined economic and environmental advantage. The model in Medini et al. (2011) [17-MCPC] aimed to map the MC enterprise's interrelationships with the external environments. Corti et al. (2011) [6-MCPC] proposed a "sustainable mass customized reference framework", setting out the (interdependent) steps involved in product, production system and supply chain design. The framework in Nielsen et al. (2011) [19-MCPC] drew together eco-design principles and modular product architectures. Sakao et al. (2005) [24-MCPC] proposed that sustainability must be tackled earlier on in the design process if dematerialization is a goal, describing a tool aimed to help planners focus more on "customer value". Souren (2003) [25-MCPC] addressed the end-of-life stage, presenting a discussion on the barriers to and enablers of closed loop MC processes in order to re-orient MC practice towards a "recovery economy".

While the above frameworks involved qualitative descriptions, Wijekoon and Badurdeen (2011) [29-MCPC] and Letmathe (2003) [14-MCPC] suggested that quantifying factors offers managers better strategic tools for evaluation and application. In the former, the model incorporated a wide set of performance metrics for a sustainable MC business model. In the latter, eco-efficiency was translated into a costing method to tackle the challenges involved in ranking or weighting environmental impacts.

In sum, all papers in this section were geared to an operations management MC audience and all represented conceptual explorations with little or no testing reported. What was especially salient was the producer–consumer relationship in these representations of distributed production: these were clearly producer centric and only [24-MCPC] aimed to bring the sustainability analysis further upstream, before the product/service idea was even born. Closing resource loops was also a recurring concern, which will be discussed further in Section 4.3.

4.2.2.3. Product design. Another notably consistent theme of topical focus and audience connected papers *by* design researchers speaking mainly to an audience *of* product designers. This sub-category is nevertheless the most heterogeneous, encompassing journal articles and conference papers, empirical studies and propositional explorations. Distributed production for these authors was mainly understood as the ability to personalize products via digital production, but this was also heterogeneously explored: consumer input in these studies ranged from, for example, providing body measurements for bespoke fashion apparel to actually making or assembling garments themselves from kits or open source designs.

For Diegel et al. (2010) [8-JSD], in a conceptual article, environmental sustainability is better ensured when designers follow eco-design principles but also strive to create "*lasting* objects of desire, pleasure and *attachment*" [emphasis added]. For these authors additive manufacturing technologies enhance designers' expression and thus "design quality", leading in turn to more pleasing products. AM is also highly suited to customizing products according to "customer needs" (which were unspecified here). This potentially leads to a greater attachment to the product which will therefore be used longer and not thrown away prematurely. This is described and emphasized here as a 'formula', as it was a recurring theme in this category as well as a cross-cutting theme among several categories (see Section 4.3.1).

Black and Eckert (2007) [3-MCPC] and Black et al. (2010) [4-MCPC] also focused on the design process, in a project description where the ultimate aim was to create fashion apparel that is more likely to be cherished and kept. Niinimäki (2010) [20-MCPC] likewise proposed that designers can effect person-product attachment and thereby product longevity but paid greater attention to the sociological and socio-cognitive understanding of this attachment (the "customer needs" that were unspecified above).

In this sense, [20-MCPC] saw beyond the technologies to the potential of the new practices or even business models afforded when designers (also) learn to engage with the consumer in new ways. Ballie and Delamore (2011) [2-MCPC] touted this new interaction as "co-creation", where "design experiences" matter as much as a well-designed garment in their conceptual exploratory paper. Niinimäki and Hassi (2011) [21-JCP] described these novel interactive fashion practices in more detail, discussing how the current unsustainable fashion industry can effect changes that are both environmentally beneficial and acceptable to consumers (according to survey results).

These design papers were thereby the most consumer oriented of all reviewed papers (and categories). Even so they did not neglect the production side, whether this entailed inclusion of eco-design considerations or touting the benefits of digital manufacturing technologies in promoting product longevity. Moreover, while the term *prosumer* was seldom used, the notion of new activities and business models that involve consumers/users in radical new ways arose as significant in this category.

4.2.2.4. Other. The final group in the Mass Customization category collects four studies that addressed other concerns or audiences than the three sub-categories above. For Steffen and Gros (2003) [26-MCPC], digital fabrication (of furniture) as local, distributed production was hypothesized to support sustained employment and regional development while avoiding transportation impacts. Fogliatto et al. (2012) [11-IJPE] presented a widely cited literature review on mass customization, where environmental implications were presented as a marginal but "promising" area of future research linked to "MC value".

For de Brito et al. (2008) [7-IJPE], examining attitudes in the fashion industry, customization was an emerging area of interest. However in this study customization and sustainability were not explicitly linked and were simply co-existing concerns for more sustainable supply chains. Finally, the only engineering-led study to adopt the term "prosumption" was Fox and Li (2012) [12-TFSC], whose framework for roadmapping material technologies was aimed especially at entrepreneurs and regional development authorities, to better determine what technologies support "sustainable" prosumption practices. A key issue for the authors was the localization of production and materials that corresponds with lower transport emissions. This issue will be further addressed in Section 4.3.3.

4.2.3. Fabbing

The third main category in this review is that of Fabbing, personal fabrication and peer-to-peer production employing digital fabrication equipment (Table 4). In two papers fabbing was an explicit facilitative component in more sustainable production and consumption patterns: in Manzini (2009) [15-DS] (as "distributed systems" of production) and Pearce et al. (2010) [22-JSD] (referring to 3D printing technologies and Fab Labs). In both papers fabbing or peer production was seen as a way to empower local communities and encourage responsible use of local resources (physical and social). In this sense, both papers (explicitly in the former, implicitly in the latter) sought to flag up the *resilience* that characterizes *distributed* networks. This association thus connected network agility with socio-ecological sustainability in a larger scale, in contrast to the simpler production agility supporting socio-economic sustainability more often implied in the previous sub-categories.

The third paper in this section, von der Gracht and Darkow (2010) [29-IJPE], addressed "fabbing" directly but did not explicitly espouse it as a route to less environmental impact. Rather the focus was on how (or if) fabbing will affect logistics, manufacturing and supply chains in part of a Delphi study. Fabbing was included as an unexpected or surprising scenario that, while unlikely, could "revolutionize production fundamentally", especially for "less complex consumer goods".

Section 4.2 has summarized the topical categories of the reviewed papers and especially drawn attention to how researchers have connected the distributed production practice – its specific characteristics as distinct from mass production – to its sustainability potential, whether this is tied to dematerialization potential of the technologies or reduced impacts due to localization. Moreover this potential may be embedded in the new relationship between producer and consumer (and the nature of the consumer 'input'), but it is mainly the design papers that examine this relationship among consumer, producer and product more profoundly. The following section will summarize the main umbrella themes that emerged from the analysis.

4.3. Cross-cutting themes

Subsequent to categorization, the analysis phase aimed to identify and collate salient cross-cutting themes that delved deeper into the research questions. These themes are listed in Table 5 in random order. The most compelling themes are described in this section, in terms of best representing the research material in this review but also highlighting key assumptions that deserve further scrutiny.

4.3.1. Product longevity

As seen in Section 4.2.2.3, a notable number of authors in this review were concerned with extending product life spans, suggesting how to combat psychological obsolescence by design via personalization.[7] For several other authors, the focus was less on the consumer and more on the producer: how end-of-life (EOL) can best be tackled in the mass customizer's business model and how personalization both enables and problematizes recovery.

Commonly mentioned issues were the difficulty to reuse individualized products, on the one hand, and the ability to incorporate disassembly in modular architectures on the other (e.g. in [6-MCPC]). [23-MCPC] discussed these enablers and barriers according to various EOL strategies such as remanufacturing or recycling. [25-MCPC] emphasized the importance of stronger communicative and "learning" relationships between consumer and producer in MC.

Use intensity was a related concern in several papers: [25-MCPC] pointed out how the sense of ownership of personalized products would problematize any product sharing or "eco leasing" solution that could better ensure higher use intensity. [14-MCPC] hypothesized that a product tailored to a consumer's needs will be used more, thereby decreasing the environmental impact "per service unit". The notion of Product-Service System (PSS), where the consumer is offered a function rather than a product in order to optimize resource use (Mont, 2002), was seen by several authors as a solution to these conundrums: a way to establish the business case for closing loops by personalizing the *customer satisfaction* rather than the product. PSS was mentioned as a design strategy in [21-JCP], as a business model where products are "value generating assets" in [1-MCPC] and as an operational model in [29-MCPC]'s evaluative framework.

In short, the authors seemed unsure of how to intensify the use of a personalized product if not through sharing, what exactly to customize in the product–service combination, and how to manage issues of ownership. On the one hand, PSS-oriented

[7] i.e. papers 3, 4, 8, 20, 21 and 26.

strategies can also draw attention to stakeholder relationships, novel combinations of actors to deliver satisfaction (Vezzoli et al., 2014), which may serve to meet circular economy goals. On the other hand, these studies remained mainly conceptual and untested; there is ample room for more research and practical interventions to test the hypotheses the authors raised. Empirical evidence validating our commonly held assumption that product attachment can have a positive effect on consumption patterns and material flow (i.e. absolute dematerialization) would also be beneficial.

4.3.2. Co-design

As stated throughout this review, the increasing ability of a consumer to influence what is produced is a key characteristic in the construct of distributed production. In a notable number of papers in this review, the term 'co-design' was used as shorthand to describe this interaction between consumer and producer[8] or between designers and non-designers.[9] However, the term was largely left undefined and under-explained, which was somewhat surprising.

This vagueness stimulated two further questions: first, what exactly is the nature of co-design envisioned by the authors? Secondly, who is responsible for initiating, designing, implementing and/or evaluating the co-design process in these contexts? As this is clearly an operational issue for mass customization practitioners, i.e. the "decoupling point", the review article [11-IJPE] provided more detail on how the MC field regards co-design, with research attention given especially to internet- and technology-enabled collaboration. Nevertheless the discussion seemed somewhat limited to a collection of "customer choices", and an MC research strand that uses "non-conventional technologies" to co-design with customers was described as "emerging".

In the MCPC conference papers it was mainly implied that the producer was in charge of co-design; likewise, in some of the design-centric papers, in [4-MCPC] and [26-MCPC], for instance, what is offered to the consumer remains the designers' choice. At the other end of the scale, in contrast, [15-DS]'s conception of co-design, while abstract and visionary, seemed to imply a greater allocation of agency among all parties.

A related and more relevant set of questions also arose from the papers' referencing to co-design: upon whom does the onus lie for environmental evaluation and decision-making, and how is this addressed in the conception of 'co-design'? Many of the conference papers focused on cleaner production strategies designed and implemented by the producer, i.e. the producers' responsibility. The consumers' input in 'co-design' was presented simply as 'needs', resulting in production of "only what truly adds value for customers" (as argued in [1-MCPC]). In some of the design-centric papers, it was not only the designers' responsibility to make eco-design decisions during the process but also to control the consumer's input and therefore even the definition of 'need'.

The authors in [1-MCPC], [17-MCPC] and [29-MCPC] attempted to take the discussion a step further, highlighting the need to incorporate eco-conscious choices in the product configurator or consider sustainability in the co-creation planning. This explicitly aimed not only to inform the consumer about e.g. environmental impacts in production and/or use, but also to allow both sustainability constraints *and* consumer need dictate *what* is actually produced as opposed to what is merely customized. In the journal papers, [21-JCP] described a wide range of co-design options, which in turn implied a variety of ways producers, designers and consumers can share both environmental information and responsible decision-making, including what is produced. In [15-DS] the whole purpose of 'co-design' was to co-create sustainable solutions and knowledge about them.

4.3.3. Local production

For all papers explicitly mentioning 'local' issues, the main sustainability benefit was avoidance of environmental impact related to transport. For the authors of [12-TFSC], local production was a success factor integral to the "expansion of prosumption". In [22-JSD], local materials and solutions to local needs, enabled by open source 3D printers, were important in the global South, where resources, skill bases and access to global supply chains are often limited.

However, further research on changing supply chains, for instance, would clarify if, how and when decentralizing production reduces negative environmental impact. [5-MCPC], for instance, pointed out that despite popular assumption, mass customization often occurs far from the customer in practice. Moreover the logistics experts surveyed in [28-IJPE] did not find it probable that the "decentralised production of many goods on-site in small-scale factories" would lead to significant structural changes for the logistics industry in 2025.

4.3.4. Technology affordances

The final cross-cutting theme was a category where authors aimed to capture the 'nature of the process' or what they believed to what ends a technology (or process or material) best lent itself, a category later called 'technology affordances'. Digital manufacturing was of particular interest to several authors with respect to what it affords, technically and materially, as well as environmentally.

For [12-TFSC], this was the core of their study: how material technologies promote particular production and consumption patterns. From the design point of view, [8-JSD] and [26-MCPC] focused on how designing for additive manufacturing differs from designing for mass production aesthetically and structurally. For these authors, the environmental benefits of designing and producing using AM technologies were clearly related to emotional attachment and product longevity. For the papers solely concerned with AM technologies, as described in Section 4.2.1, material saving was especially emphasized as an environmentally relevant benefit, while [10-RPJ] also highlighted the role of AM *prototyping* as a design tool to better ensure consumer acceptance and less waste.

The AM-centred papers revealed other compelling implicit and explicit issues. In [13-JCP]'s study of energy consumption, for instance, an optimal low energy density range for SLS was identified, which further offered the possibility to eliminate the preheating phase. The authors in [18-RPJ] drew attention to AM equipment design that in one case actually reduces manufacturing time, as the software identifies the longest diagonal and starts at that point. This led to reduced electricity consumption. In [9-RPJ], the authors pointed out that manufacturers' specifications for powder use are generally followed in the industry but tend to lead to unnecessary waste. The authors did not discuss the implications further, but one could put forward that AM equipment manufacturers themselves could pursue research and development of technologies that enable their users to operationalize more environmentally responsible practices.

4.4. Synthesis

To further synthesize the findings discussed in the previous sections, a concept map (Hart, 1998) was created (Fig. 4). It is important to note that the map is proposed as a tool for locating

[8] i.e. in papers 1, 6, 11, 17, 21, 26, 29.
[9] In papers 2, 4, 15.

current and emerging distributed production activities *and* research, where the quadrants are not viewed as having clear borders but rather as a continuum. Further research can serve to validate the axes chosen or evolve them as circumstances change.

4.4.1. The distributed production landscape

The two extremes of the construct 'distributed production' most discussed in the literature, and most visible in current real-life activities, were placed in the bottom left and top right quadrants (Fig. 4). As a reminder that distributed production activities are both commercial and conducted for non-economic reasons, the labels 'market influence' and 'non-market influence' were inserted at the two extremes. At bottom left, therefore, representing activities nearest the current dominant mass production paradigm, 'mass customization' at its extreme aims to retain control over consumer input (i.e. the producer retains the final decision on what is personalized and how, likely for cost and market reasons). Personalization is therefore 'batch' and modular rather than unique and volumes are relatively large. The papers in this review discussing mass customization were placed in this quadrant.

At top right, in 'personal fabrication' an individual produces her own artefacts (e.g. in a Fab Lab or 'maker space'). She has full agency and authority over both design and fabrication, which depends only on her own competence. Scales are small: facilities, volumes and equipment. It is assumed the authors in the Delphi study, [28-IJPE], had this conception of 'fabbing' in mind and aimed to elicit from the experts how likely this would spread, e.g. shift towards the bottom right quadrant.

The top left and bottom right quadrants were less obviously represented in the reviewed literature and, to the researcher's knowledge, see less representation in real-life activities. They have therefore been accorded working titles and descriptions based on their positions on the axes. In the bottom right, we must imagine personal fabrication on a larger scale ('mass fabrication'), likely the material version of Web 2.0 peer content development and sharing visible today. The emphasis remains on the individual's authority over what is designed and made (i.e. a truly peer-to-peer arrangement). This accords with the conceptions of distributed production proposed in [15-DS] and [22-JSD], and, given the variability in consumer input in the design services described in [21-JCP], it is placed in the middle of the scale.

In the top left quadrant, the scale is 'small' and therefore the level of personalization can result in one-offs and bespoke services. Nevertheless the producer retains authority over what is produced and what consumer input is needed. This conception of 'bespoke fabrication' is influenced by the vision of prosumption presented in [12-TFSC], and the authors' conception of "neo-craft" "technofacture" proposed in [25-MCPC] may also be placed here.

4.4.2. The environmental sustainability of distributed production

The final synthesis task returned to the question of how the authors see the relationship between distributed production and environmental impact, superimposing the opportunities onto the previous 'landscape' (Fig. 5). Beginning in the 'mass customization' quadrant, the authors reviewed saw the main environmental benefits as the capacity to avoid the pre-consumer waste seen in mass production (especially in the fashion and clothing industry), to enable recovery and create closed-loop systems, and to incorporate sustainability-led parameters in the product configurators. They also saw these benefits as conditional upon the ability to exploit the stronger consumer–producer relationships and modularity in MC models.

In comparison, the authors envisioning a more 'bespoke fabrication' construct tended to emphasize how 'small' means 'local' and therefore fewer emissions and impacts from transport. Bespoke products were also assumed to entail less overall material and energy use as they would be used longer and/or more intensively and be less vulnerable to mechanisms of technical, aesthetic, functional and/or psychological obsolescence. However, many authors highlighted the need for high quality to ensure pleasurable associations and therefore attachment as well as functional longevity.

In 'personal fabrication' in the top right, authors also emphasized the benefits of localizing both production and materials. Research in rapid prototyping confirms that a fabbed artefact may have relatively high environmental impacts per unit, but at this personal scale overall volumes remain very low. When the scale is increased in the 'mass fabrication' construct, in the bottom right,

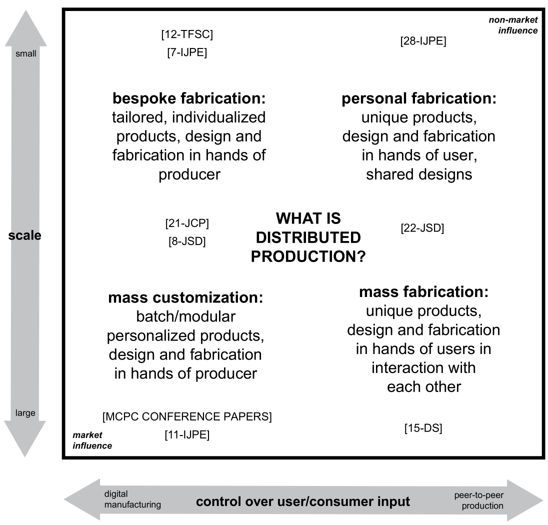

Fig. 4. Conceptualizing the distributed production landscape.

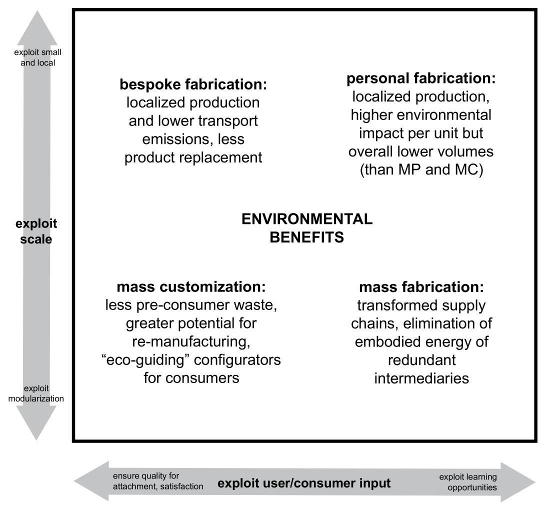

Fig. 5. Opportunities to promote environmental sustainability in distributed production: summary of the authors' propositions.

Table 1
Key to articles and source abbreviations.

No.	Article	Journal/Conference	Reference
1	[1-MCPC]	World Conference on Mass Customization and Personalization (MCPC)	Badurdeen et al., 2010
2	[2-MCPC]	MCPC	Ballie and Delamore, 2011
3	[3-MCPC]	MCPC	Black and Eckert, 2007
4	[4-MCPC]	MCPC	Black et al., 2010
5	[5-MCPC]	MCPC	Chin and Smithwick, 2010
6	[6-MCPC]	MCPC	Corti et al., 2011
7	[7-IJPE]	International Journal of Production Economics (IJPE)	de Brito et al., 2008
8	[8-JSD]	Journal of Sustainable Development (JSD)	Diegel et al., 2010
9	[9-RPJ]	Rapid Prototyping Journal (RPJ)	Dotchev and Yusoff, 2009
10	[10-RPJ]	RPJ	Drizo and Pegna, 2006
11	[11-IJPE]	IJPE	Fogliatto et al., 2012
12	[12-TFSC]	Technological Forecasting and Social Change (TFSC)	Fox and Li, 2012
13	[13-JCP]	Journal of Cleaner Production (JCP)	Franco et al., 2010
14	[14-MCPC]	MCPC	Letmathe, 2003
15	[15-DS]	Design Studies (DS)	Manzini, 2009
16	[16-RPJ]	RPJ	Marchelli et al., 2011
17	[17-MCPC]	MCPC	Medini et al., 2011
18	[18-RPJ]	RPJ	Mognol et al., 2006
19	[19-MCPC]	MCPC	Nielsen et al., 2011
20	[20-MCPC]	MCPC	Niinimäki, 2010
21	[21-JCP]	JCP	Niinimäki and Hassi, 2011
22	[22-JSD]	JSD	Pearce et al., 2010
23	[23-MCPC]	MCPC	Petersen et al., 2011
24	[24-MCPC]	MCPC	Sakao et al., 2005
25	[25-MCPC]	MCPC	Souren, 2003
26	[26-MCPC]	MCPC	Steffen and Gros, 2003
27	[27-RPJ]	RPJ	Telenko and Seepersad, 2012
28	[28-IJPE]	IJPE	von der Gracht and Darkow, 2010
29	[29-MCPC]	MCPC	Wijekoon and Badurdeen, 2011

we imagine that supply chains may be transformed and movement of materials and components more prevalent than finished consumer products (as suggested in [28-IJPE]). Some authors (especially [5-MCPC]) highlighted the embodied energy in retail and other infrastructure that would not be expended in these changed distribution arrangements. With regard to how consumer involvement can influence the environmental impact of peer production (i.e. the horizontal axis), the papers reviewed rather abstractly referred to the indirect environmental benefits of knowledge and capacity building.

5. Discussion

Discussing the implications of this study must take into account the two objectives of the review. The first is to map the landscape of research, i.e. who is discussing distributed production and who is not (research questions 1 and 3), and the second, its contents: if distributed production can enable the dematerialization of consumption (research question 2).

5.1. Hypotheses on environmental benefits

The first contribution of this paper is the summary of distributed production as seen in Figs. 4 and 5: what distributed production entails, and why and how these activities are seen to lead to more sustainable socio-economic patterns. The patterns found in this study mainly emphasized production only according to need, stronger person-product affinities and significant connections between producer and consumer.

However, that many studies have remained conceptual (and – among this group – often seemed to remain as conference papers and not turned into full journal papers) is currently a hindrance to an evidence-based view of the phenomenon. There is need for more empirical data, and from more fields than design and engineering.

Because the reviewed papers have come forth from mainly the engineering and production planning professions, this has created a rather one-sided view on the consumer–producer relationship that seems to stress only communications. As more laypeople gain access to manufacturing technologies, however, this relationship is becoming more complex. The true value of 'co-design' needs to be further unpacked in both research and practice, as it appears to be a key factor differentiating distributed production from the mass production mode. One-sided 'cleaner production' is not enough: production and consumption must be evaluated together. A strategy of cleaner prosumption reconsiders not only *how* something is produced, but *what* is produced (or prosumed) and why.

There is hence need for discussion on the valuing systems behind distributed production activities involving material goods. This would serve practical, operational objectives and clarify the axiological underpinnings. Many disciplinary and epistemic

Table 2
Summary of Additive Manufacturing Processes category.

Sub-category	Article	How distributed production is represented	Sustainability: defining, measuring operationalizing	Main sustainability issue addressed	Research field, audience
Energy	[13-JCP]	Rapid Prototyping (RP) technologies for prototyping: Selective Laser Sintering (SLS)	Theoretical optimal process energy measurement	Energy consumption of production optimizing dimensional accuracy	Operations and production management
	[18-RPJ]	RP technologies in manufacturing parts: SLS and 3D Printing (3DP)	ISO 14000 as an example	Reducing electricity consumption	Operations and production management
	[27-RPJ]	Additive Manufacturing (AM) technologies (SLS) in manufacturing parts	Life Cycle Inventories (LCI), comparing AM with mass production (injection moulding)	Energy consumption of production	Operations and production management
Recycling	[9-RPJ]	RP technologies (SLS) for prototyping with potential for manufacturing (RM)	Material management and recycling	Cost savings, quality assurance prioritized but environmental implications if RM expands	Operations and production management
	[16-RPJ]	RM technologies for producing objects/parts: 3DP	Recycled glass powder experimentation	Recycled glass for "sustainable future for 3DP"	Operations and production management
Environmental impacts	[10-RPJ]	RP and Rapid Tooling (RT) for prototyping and enabling Mass Customization (MC)	Industrial Ecology (IE), Environmental impact assessment (EIA), Life Cycle Assessment (LCA)	RP materials, especially toxicity	Operations and production management

Table 3
Summary of Mass Customization and Personalization category.

Sub-category	Article	How distributed production is represented	Sustainability: defining, measuring operationalizing	Main sustainability issue addressed	Research field, audience
Sustainability of MC	[1-MCPC]	Mass Customization (MC)	Triple Bottom Line, '6Rs' approach, Sustainable Supply Chain Management	Product-Service System (PSS) to enable closed loops	Operations and production management
	[5-MCPC]	MC	Life cycle analysis of energy and material use	Embodied energy analysis in MC compared to mass production (MP)	Operations and production management
	[23-MCPC]	MC	End-of-Life strategies, eco-design, life cycle thinking	MC sustainability gains compared to MP	Operations and production management
Frameworks and models	[6-MCPC]	MC	Sustainable MC criteria (product architecture, manufacturing, supply chain)	MC as route to (environmental) sustainability through e.g. less waste and inventory	Operations and production management, Design and engineering
	[14-MCPC]	MC	Eco-efficiency and eco-effectiveness, "CML concept"	Eco-Efficiency through efficiency costing	Operations and production management, Environmental management
	[17-MCPC]	MC	Social, economic, environmental dimensions in enterprise assessment; stakeholder assessment	Enterprise interrelationships (with society and environment)	Operations and production management
	[19-MCPC]	Mass Customization, Personalization and Co-creation (MCPC)	'Ten Golden Rules of Eco-Design'	Sustainability through modularization	Operations and production management, Design and engineering
	[24-MCPC]	MC	Service Engineering tool to ensure customer satisfaction and in turn dematerialization of products	Value creation and customization through customer satisfaction	Operations and production management, Design and engineering
	[25-MCPC]	Mass Customization and Personalization (MCP)	"Double layer closed loop model"	Recovery and closed loop opportunities and barriers in MCP	Operations and production management, Environmental management, Design and engineering
	[29-MCPC]	MC	6R methodology, PSS design approaches to promote dematerialization	Modelling framework to evaluate product and PSS configurations	Operations and production management, Design and engineering
Product design (fashion)	[2-MCPC]	"Co-creation", "user-based tools for discovery, creation, production and sharing"	Design approaches such as "emotionally durable design", "co-design", "open source design"	Strengthening relationship between fashion designer and customer to reduce e.g. waste	Design and engineering
	[3-MCPC]	Personalization and customization through (in part) rapid prototyping technologies	"Considerate Design Footprint" to assess costs and risks including environmental impacts	Considering environmental impacts in product design stage	Design and engineering
	[4-MCPC]	Personalization through (in part) rapid prototyping technologies	Personalized fashion to ensure fit and comfort and in turn extended use	Reducing product replacement, consumption via engagement and empathy	Design and engineering
Product design (textiles)	[20-MCPC]	Customizing via digital (textile) technologies	Product longevity via uniqueness	Fostering product-person attachment	Design and engineering

(*continued on next page*)

Table 3 (*continued*)

Sub-category	Article	How distributed production is represented	Sustainability: defining, measuring operationalizing	Main sustainability issue addressed	Research field, audience
Product design (clothing and textiles)	[21-JCP]	MC, "co-creation", halfway products	Business models that focus on user satisfaction and outcomes	Design strategies to extend product life span	Design and engineering
Product design	[8-JSD]	MC with the help of Additive Manufacturing (AM)	MC product design and AM manufacture to create "objects of desire"	Product longevity via "design quality"	Design and engineering
Other studies	[7-IJPE]	Customized (apparel), personalized value	Sustainable supply chains and logistics, understanding benefits and barriers	Industry viewpoints where customizing is one small (competitive) aspect	Operations and production management
	[11-IJPE]	Mass Customization (MC)	Environmental implications of MC: likely to influence "dissemination and acceptance of MC technologies and methods"	Environmental and ethical issues as recent but marginal focus of study in literature, linked to value dimensions	Operations and production management
	[12-TFSC]	"Prosumption", customer "authority" over design and production	Prosumption as desirable new paradigm, framework to roadmap (sustainable) material technologies	Point-of-demand production, avoiding transportation impacts	Regional development, Design and engineering
	[26-MCPC]	MC and "art customization", decentralized production	Meeting ecological demands via sustainable regional development	New forms of furniture production bridging craft skills and digital technologies	Regional development, Design and engineering

Table 4
Summary of Fabbing category.

Sub-category	Article	How distributed production is represented	Sustainability: defining, measuring operationalizing	Main sustainability issue addressed	Research field, audience
Peer-to-peer	[15-DS]	Distributed systems, "sustainable distributed knowledge economy"	Design for sustainability that facilitates social learning process towards sustainable society	Agenda for design research to promote co-creation of sustainable solutions	Design and engineering
	[22-JSD]	Open source 3D printers as Open Source Appropriate Technology (OSAT)	Sustainable development especially poverty alleviation via appropriate technologies for local village empowerment	Open source 3D printers' characteristics and optimum future development	Design and engineering, International development
Logistics	[28-IJPE]	Fabbing in small-scale factories or at home	Environmental sustainability not connected directly to fabbing but as umbrella concern for logistics	Fabbing as a wildcard that may impact logistics, environmental impacts implicit	Operations and production management

Table 5
Salient concerns in reviewed papers.

	[1-MCPC]	[2-MCPC]	[3-MCPC]	[4-MCPC]	[5-MCPC]	[6-MCPC]	[7-IJPE]	[8-JSD]	[9-RPJ]	[10-RPJ]	[11-IJPE]	[12-TFSC]	[13-JCP]	[14-MCPC]	[15-DS]	[16-RPJ]	[17-MCPC]	[18-RPJ]	[19-MCPC]	[20-MCPC]	[21-JCP]	[22-JSD]	[23-MCPC]	[24-MCPC]	[25-MCPC]	[26-MCPC]	[27-RPJ]	[28-IJPE]	[29-MCPC]
longevity		×	×	×	×	×		×						×						×	×		×		×	×			×
co-design	×	×		×		×					×				×		×				×					×			×
design	×	×	×	×		×		×		×					×				×	×	×	×		×	×	×		×	
local		×	×	×	×							×			×					×		×	×			×		×	
PSS	×																				×								×
end of life/reuse/recovery	×				×	×			×	×				×					×			×	×		×				×
open source		×													×	×					×	×							
craft		×	×	×								×			×					×						×			
'developing' countries							×					×										×							
Network/Knowledge Society												×			×													×	
time		×			×										×					×									
future												×			×			×		×		×				×		×	
technology affordances			×	×	×			×	×	×		×	×		×	×		×			×	×				×	×	×	

perspectives, from economics and marketing to management science and organizational behaviour, may contribute to this knowledge building.

5.2. Unknown consequences

There were also environmental implications arising from the reviewed papers and their synthesis that were not discussed by the authors. Because of the heavy emphasis on frameworks and identifying environmental benefits, combined with the lack of, for instance, real-life case studies, the environmental harms (potentially) concomitant with a decentralized production paradigm remained unacknowledged. This realization resulted in the creation of a further 'landscape' of environmental concerns to supplement the previous two (Fig. 6), and the second contribution of this paper.

Firstly, the more personal fabrication becomes (i.e. the further right in the map), the more exposed the individual becomes to materials and processes and their as yet unknown properties such as toxicity. This also means it is less certain that other safety mechanisms are in place (as they would be in more established and regulated contexts such as commercial activities). The risk of harmful emissions to the environment may also be greater.

The fabrication of new types of products may additionally render them less amenable to existing consumer recycling systems, e.g. for plastics, whether because of actual material properties or barriers due to changed habits and routines. Moreover, even if some consumer products are replaced by materials in new distribution arrangements and environmental impacts associated with the retail infrastructure lessen, it is possible the production, storage and distribution of materials and components (and their inherent impacts) remain just as invisible to the consumer as the current mass production supply chain is.

On the left side of the landscape, the reviewed papers had raised the concern of reusing and recycling customized products. There are also several unstated implications: for instance it remains unclear if the high quality production needed to better ensure product longevity will involve more resources and energy that will ultimately counteract the environmental gains from longer or more

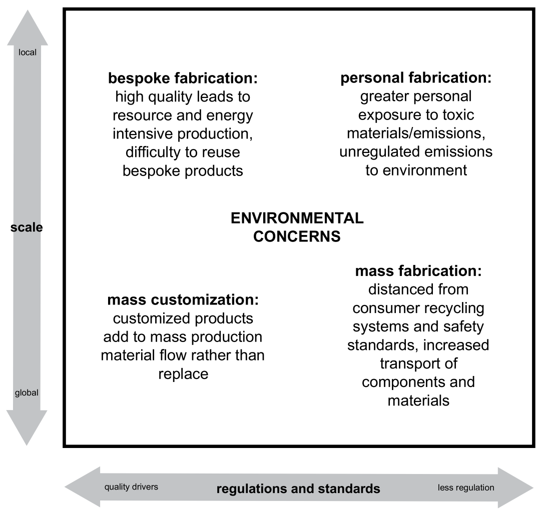

Fig. 6. Threats to environmental sustainability in distributed production (arising from but mainly not explicit in the reviewed papers).

intense product use. It is also debatable whether mass customization will replace some mass production material flow or simply add to it, not to mention the growing environmental footprint of the internet and information and communications technologies. Further observation and analysis may be able to determine how these activities play out in time – and what time and scale settings are most appropriate for study.

6. Conclusions

Distributed production holds promise of greater environmental sustainability, but it is not a given that it will be a new, clearly cleaner production paradigm. The review illuminated the opportunities for greater environmental sustainability as well as potential threats, addressing of which could serve to improve these novel, emerging practices today. The concept maps presented in the review summarize the reviewed papers' positions on environmental benefits and may also provide clues to how distributed production may be defined and delimited as more research emerges.

This study has clarified what characterizes distributed production in its different forms, what is already known or hypothesized regarding its dematerialization potential, and what topics are fruitful arenas for further examination. The conceptualization can inspire and legitimize practitioners' experiments with business models, new customer–producer relationships and novel, reconfigured prosumption networks. By flagging areas where undesired environmental impacts may arise, the review guides further research and encourages practitioners to take them into account in their current and future activities.

Acknowledgements

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Appendix A. Summary of sources: journals

Journal NAME, Dates	Total articles	Relevant	Focus (Journal's description)	Category (Journal's description)	Eigenfactor Category
Co-Design, 1(1) 2002–8(4) 2012	about 130	0	Research on nature of collaborative design from any design domain.	Collaborative Design, Design, Engineering and Technology.	n/a
Design Studies, 23(1) 2002 –33(6) 2012	about 330	1	Design activity, from cognition and methodology to values and philosophy.	Design Research in Engineering, Architecture, Products and Systems.	Robotics.
Ecological Economics, 40(1) 2002–84 2012	about 2240	0	Transdisciplinary. Management of ecology and economics. Commentaries, surveys, analyses, methodologies, ideological options.	Environmental sciences. Environmental Technology, Policy and Management, etc.	Economics.
International Journal of Production Economics 75(1 –2) 2002–140(2) 2012	about 2570	3	Multidisciplinary. Interface between engineering and management; academic approach and industrial applications.	Manufacturing and process industries, production.	Operations research.
Journal of Cleaner Production, 10(1) 2002–37 2012	about 1880	2	Interdisciplinary. Techniques, concepts and policies.	Industrial applications and Environmental Management, Legislation and Policy, Education.	Environmental Chemistry and Microbiology.
Journal of Consumer Culture, 2(1) 2002–12(3) 2012	about 160	0	Multidisciplinary. Theory and empirical.	Consumption and consumer culture. Sociology. Cultural Studies.	Sociology.
Journal of Industrial Ecology, 6(1) 2002–16(6) 2012	about 530	0	Interdisciplinary. Conceptual contributions, findings from primary research and practice.	'Industrial metabolism', 'industrial symbiosis'.	Environmental Chemistry and Microbiology.
Journal of Sustainable Development, 1(1) 2008–5(12) 2012	about 560	2	Transdisciplinary. Original research and reviews.	Environmental science, technologies, economics and policy; ecology; sustainable development.	na
Rapid Prototyping Journal, 8(1) 2002–18(6) 2012	about 415	5	Developments and applications in additive manufacturing (AM).	Mechanical and Materials Engineering.	Physics and Chemistry.
Technological Forecasting and Social Change, 69(1) 2002 –79(9) 2012	about 910	1	Multidisciplinary. Methodology and practice of technological foresight.	Technological Forecasting, Futures Studies.	Management Studies.

Appendix B. Summary of sources: conferences

Conference name	Conference description, focus year	Relevant (available full paper)	No. of sessions total	Sustain-ability sessions	No. of papers/ presentations total (in proceedings)	Sustainability papers /presentations
Additive Manufacturing Conferences	Industrialists and academics: Engineers, innovators, designers, business managers, academics and researchers, and AM materials and system developers. 'Exceptional papers' accepted.					
	2006	0	–	–	18	0
	2007	0	–	–	15	0
	2008	0	–	–	14	1
	2009	0	7	0	14	0
	2010	0	7	1	14	2
	2011	0	7	0	14	0
	2012	0	7	0	14	0
MCPC Conferences: International Conference on Mass Customization & Personalization	Interdisciplinary, scientists and practitioners. Innovation and research. Technological IT infrastructures, design applications, success stories and business models. Peer reviewed papers.					
	2003	3	14	1	117	4
	2005	1	31	0	124	4
"Extreme Customization"	2007	1	54	0	160	4
"Mass Matching: Customization, Configuration & Creativity"	2009 (Proceedings 2010)	4	29	2	95	11
"Bridging Mass Customization and Open Innovation"	2011	6	41	3	144	13
PINC Conferences: Participatory Innovation Conference	A spread in disciplines to cover innovation from several perspectives, including design, anthropology, conversation analysis, business, management, and public procurement. Peer-reviewed papers.					
	2011	0	5	0	68	2

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Anticipated environmental sustainability of personal fabrication

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ABSTRACT

Distributed manufacturing is rapidly proliferating to citizen level via the use of digital fabrication equipment, especially in dedicated “makerspaces”. The sustainability benefits of citizens' personal fabrication are commonly endorsed. However, to assess how these maker practitioners actually deal with environmental issues, these practitioners and their practices need to be studied. Moreover research on the environmental issues in personal fabrication is nascent despite the common perception that the digital technologies can become disruptive. The present paper is the first to report on how practitioners assess the environmental sustainability of future practices in this rapidly changing field. It does so through an envisioning workshop with leading-edge makers. The findings show that these makers are well able to envision the future of their field. Roughly 25% of the issues covered had clear environmental implications. Within these, issues of energy use, recycling, reusing and reducing materials were covered widely by environmentally-oriented participants. In contrast, issues related to emerging technologies, materials and practices were covered by other participants, but their environmental implications remained unaddressed. The authors concluded there is a gap between different maker subcultures in their sustainability orientations and competences. Further research on the environmental aspects of real-life maker practices and personal fabrication technologies now could help avert negative impacts later, as the maker phenomenon spreads. This knowledge should also be directed to developing targeted environmental guidelines and solutions for personal fabrication users, which are currently lacking. Potential also lies in seeking to enhance dialogue between pro-environmental and new-technology-oriented practitioners through shared spaces, workshops and conferences.

1. Introduction

Certain groups of end-users, often called “makers”, are increasingly involved in the design and production of their own products (Raasch and von Hippel, 2012; Anderson, 2012). This transition is enabled by greater access to digital manufacturing technologies at home, through services or in dedicated spaces (i.e. “makerspaces”). Such access is regarded by many as a disruptive alternative to mass production and consumption through material “peer production” (Benkler, 2006; Bauwens et al., 2012) or “personal fabrication” (Gershenfeld, 2005). There are potential environmental benefits, and harms, to distributing production in this way, but these have been little studied to date (Kohtala, in press).

If these personal fabrication practices diffuse into wider society, it is important to clarify the direct environmental impacts of technologies and materials, but also their indirect effects on society and consumption patterns. For instance, the “maker movement” is often promoted as more environmentally benign than mass production, by enhancing skills to build and repair, answering one's own needs as opposed to “satisficing” through passive consumption, and distributing production within local networks as opposed to long, large-volume supply chains (Diegel et al., 2010; Niinimäki and Hassi, 2011; van Abel et al., 2011). How maker practitioners organise their activities may provide a leverage point for more sustainable practices, depending on the makers' own knowledge of environmental impacts and how they enact sustainability-oriented values.

These hypotheses about the current and future sustainability of making are, however, currently based on limited scientific evidence, and maker practitioners tackle these questions of environmental sustainability based on their professional skills. This raises the question of maker practitioners' knowledge: how wide and

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deep is their own awareness of the environmental implications of making, and do they operationalise it in their current practices as well as planning for future activities?

The authors have earlier investigated these topics through long-term ethnographic research, examining the daily practices of setting up new makerspaces and organising and conducting making activities. This appears helpful in discerning the gaps between actors' pro-environmental attitudes and their concrete practices (e.g. Kohtala and Bosqué, 2014). However, making is a rapidly changing phenomenon where environmental implications may change and evolve as new technologies and interests emerge. The research question in the present paper is therefore:

What issues do competent maker practitioners foresee in the environmental sustainability of near future makerspaces?

To assess this, a workshop was organised with leading-edge practitioners in Finland. It was designed carefully so the practitioners were working on a real project, but also to offer a clear view on if and how they would consider issues related to the environmental sustainability of makerspaces in 2020. The year 2020 was a target date close enough for the practitioners to voice reasoned propositions about, but also far enough in the future to push them to envision likely future developments in this rapidly changing field and indicate any related environmental effects. The reasoning behind the workshop structure and its context is explained in section 3, as well as the methods for analysing the results. The findings and their implications are summarised in sections 4–6. Section 2 provides more background on the maker movement and personal fabrication, with special emphasis on shared makerspaces and the knowledge on sustainability issues to date.

2. Background

Although "making" builds on a tradition of handicraft and "DIY" (do-it-yourself), it today also includes (and more commonly refers to) use of digital tools in hands-on fabrication of material artefacts, including electronics and physical computing experiments, stickers and marketing items for small businesses, furniture and items for the home or body, and prototypes of all kinds. Shared makerspaces are workshops with low-cost digital fabrication equipment, typically milling machines for making circuits or casting moulds (using wood, silicon, wax and plaster); vinyl cutters; desktop 3D printers (typically using ABS and PLA plastics); laser cutters (for usually plywood, cardboard and acrylic); and often electronics workstations for microprocessor programming and project prototyping.[1] Product designs (often shared digitally) are realised by the users themselves and, due to their digital form, can be designed together with peers in other locations.

Makerspaces include fab labs, which are workshops in MIT Center for Bits and Atom's network (Gershenfeld, 2005); hacklabs or hackerspaces for exploring electronics (Maxigas, 2012); commercial machine shops offering paid access to members; and a variety of other spaces that may be independent or associated with a library or museum, typically having less of the heaviest equipment such as large CNC machines (Troxler, 2011). The number of makerspaces worldwide is growing rapidly: to date there are over 450 fab labs and 1000 active hackerspaces (FabLabs, 2015; HackerspaceWiki, 2015), listings that do not account for independent spaces. There is currently scant research on who uses makerspaces and how exactly (e.g. Ghalim, 2013; Maldini, 2013), but the practitioner view is that there is considerable variation, from students in university fab labs to entrepreneurs to hobbyists who dominate hackerspace-type facilities (e.g. Eychenne, 2012; Toombs et al., 2014).

Reports on the sustainability of personal fabrication are emerging as the phenomenon spreads, often appearing as grey literature (De Decker, 2014; Olson, 2013). The few empirical studies that exist mainly focus on additive manufacturing, relevant to some digital fabrication equipment, such as studies on energy consumption and Life Cycle Analyses (e.g. Baumers et al., 2013; Faludi et al., 2015). When compared to mass production processes, digital manufacturing has the potential to reduce material, waste and energy, at least for small batches (ATKINS Project, 2007), and may mitigate negative impacts connected to supply chains (Huang et al., 2013). However toxicity of especially additive manufacturing materials remains a concern (Drizo and Pegna, 2006; Short et al., 2015), as well as the high energy consumption of digital fabrication.

In addition new DIY strands are exploring areas such as citizen science and urban agriculture, activities conducted in their own communities and spaces or included in the repertoire of already established makerspaces (Tocchetti, 2012). The environmental and human impacts of Do-It-Yourself Biology ("DIYbio", "biohacking" or "DIY-pharma") (Delfanti, 2013) are as yet unknown, but these practices are increasing in uptake and variety.

These environmental issues are summarised in Fig. 1. Given all these uncertainties, affecting how personal fabrication develops from early on appears preferable to simply having to face whatever negative impacts materialise later.

3. Data and methods

The data for this study were drawn from a collaborative design experiment where thirteen leading Finnish maker experts were recruited to elaborate the future of makerspaces for the year 2020. The stakes of the workshop were real: the host was Helsinki library services, who will build a public makerspace for its flagship city centre library that will open its doors in 2018, as well as a small-scale pilot space that opened a few months after the workshop. The local maker communities would be among the prime users of such facilities.

The workshop was designed to combine elements from lead user workshops (Herstatt and von Hippel, 1992; Churchill et al., 2009) and participatory design (Greenbaum and Kyng, 1991; Bødker et al., 2004; Hyysalo et al., 2014). Both the library personnel and the researchers sought practical information about future makerspaces but also raised discussion on sustainability, which was then highlighted in further analysis.

Similar futuring exercises have been conducted using, for example, participatory backcasting (Mont et al., 2014). Stakeholder collaboration was also seen as integral to learning and transition in urban transformation processes (McCormick et al., 2013). Furthermore peer-to-peer making practices are among the "grassroots innovations" that are rarely included in foresight exercises and innovation programmes but would have much to contribute (Smith et al., 2014; Hyysalo et al., 2013a,b, 2014).

The desired participants were identified by first listing the relevant maker communities, sectors and fields of expertise that would provide a diverse set of perspectives on the present and future of personal fabrication and makerspaces. The sectors, commercial, academic, third sector and local authorities, were further sub-divided into fields such as ICT, engineering, digital fabrication, "hacking", "crafts" and "support organisations". Both organisations and individuals were identified in the authors' contact networks (having been embedded in the Finnish maker scene for several years), in discussion with the library personnel and through snowball sampling. This resulted in a list of 32 individuals, many of

[1] For MIT's recommended Fab Lab inventory list, see Fab Foundation (2015).

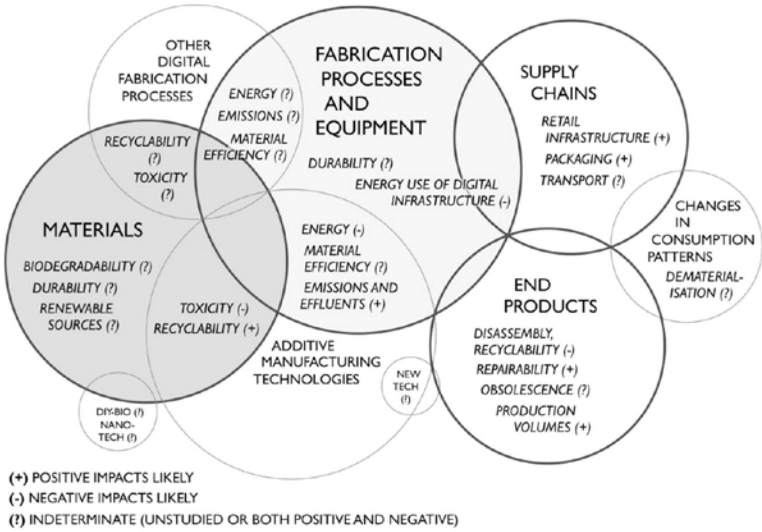

Fig. 1. Broad overview of the environmental issues in personal fabrication and makerspaces. Most empirical research to date appears in the grey coloured topics.

whom were involved in more than one relevant field or sector. The list was compiled so that each of the competences sought after for the workshop would be held by at least two invited individuals. The workshop date suited 13 participants, who upon a further check presented a balance of male and female and most importantly represented all the competencies desired. Taken together they held wide and deep knowledge on different facets of digital fabrication, shared workshops, open innovation and peer-to-peer dynamics, as well as experience in organising and facilitating participatory events, including making-related events, environmental activism and urban gardening, and peer learning.

In the workshop the first three hours concentrated on trend identification and final three hours on solution concretisation. Both parts relied on participants writing their statements on pre-categorised post-it notes, drawing from participatory design ideas of representing work through prefilled cards (Muller, 1993) and inspiration cards (Halskov and Dalsgaard, 2006). The categories on the cards reflected the issues most likely to be salient in considerations about the future of making and makerspaces based on prior research: "Technology", "Activities", "Sharing/Organizing/IPR", "Safety & Risks", "Other" and in the last three parts of the workshop "Sustainability".

In the first phase of the workshop the participants had 30minutes to list the most important trends in making for the year 2020 and were then asked to share the three most important trends they had written. This was followed by an exercise where all participants starred which of the "top three" trends they felt were most important (not their own) to ensure an explicit understanding of which issues the participants themselves wished to emphasise.

The afternoon part of the workshop was designed to identify which trends could be concretised and were not merely the proposers' wishful, fantastic or ideological expressions of the future, lacking notions of what they could mean. These exercises were conducted in the same-sized makerspace (Aalto Fablab, Helsinki, Finland) that was to be built in the central library, and the participants were instructed to start adding post-it notes directly onto its machines and surfaces to make it the future 2020 makerspace. This phase drew from experience in "participatory full scale modelling" (Hornyanszky Dalholm, 1998) to help people achieve a "hands-on future" (Ehn and Kyng, 1991).

This workshop set-up was arranged to produce several types of data. A continuous audio recording with four separate recorders and two video recorders covered most talk and interaction taking place in both settings. As the number of people in these set-ups was relatively high (22, i.e. 13 participants, 4 facilitators, 6 library planners following the event), and particularly for the afternoon sessions when the participants dispersed to parallel actions and talk sequences, the audio and video data became challenging to transcribe and was rather used as a back-up repository, to verify issues that remained unclear with less intensive documentation methods.

The next layer of the documentation was photographs, which facilitators and library personnel shot continuously of the process and outcomes of the workshop. Altogether 691 photographs record every post-it written and the sequence in which they emerged, providing a still picture trace of the workshop flow. The written post-it notes, 495 in total, were the next layer of outcomes. Finally, each of the facilitators made fieldnotes after the day to record their observations of the dynamics between participants and participant reactions to the processes, materials and outcomes during the workshop.

The analysis of the data proceeded in several phases. The statements on post-it notes, codes therein, the author of each statement and their placement and sequence in the events were tabulated for the 188 trend statements and the 307 solution statements, along with if they had been ranked among the three most important and those voted by others. Seven trend statements were reclassified as solutions and three solutions were discarded as too abstract and ambiguous. Several statements were remarkably similar, and these exact matches were combined to form one statement.

The next analysis phase focused on how explicitly practitioners dealt with sustainability issues in makerspaces and personal fabrication. The statements were examined to determine which ones related to a positive or negative sustainability issue and which ones had no clear relevance to environmental impact. The

Table 1
Examples of "Top 3" Technology trends and their sustainability coding.

Category	Post-it contents	Location 0 = other wall, 1 = top wall (Top 3), no. of stars given by other participants	Sustainability 0 = No obvious sustainability implication 1 = Implicit sustainability (researchers' interpretation) 2 = THEY express sustainability
Technology	Big data + open data + co-creation = new opportunities	1 (*)	0
Technology	Nano material will arise in making	1	1
Technology	Waste management sites: sorting stations will scan all the waste and scanned items will be "networked", directed to X by request	1 (***)	2

sustainability-related statements were further coded according to if the participant had directly expressed the environmental concern, for instance, on a Sustainability post-it or in terms related to environment, waste, energy or other clear, unambiguous expressions. Several statements, however, had a clear environmental implication (Fig. 1) that was not expressed by the participants, and these statements were also marked (see Table 1). To ensure a robust discussion on what entailed a clear sustainability implication as well as a clear expression of sustainability concern by the participants, the two authors coded all the statements independently and then compared the coding in three consequent discussions. Most codings were uniform but twelve borderline items required the three rounds of deliberation. In the end five statements were discarded from further analysis as too ambiguous.

Finally, the trends and solutions were grouped respectively in thematic clusters, first general themes and then themes according to sustainability relevance. The sustainability-relevant statements were isolated and were placed into a logical property space, matching trends and solutions, an analysis that will be described further in section 5 and where the main findings of the current study reside.

4. Findings: the distribution of identified trends and solutions

The final data set yielded 177 trend statements and 262 solution statements. This section will briefly present the overview of workshop outcomes as necessary background information to discussing the results of the deeper analysis in section 5.

4.1. Trends

The themes addressed by the trend statements are illustrated in Fig. 2. The trends were distributed among the pre-determined categories quite evenly (16–23% falling to each category), as can be seen in Fig. 3 (left). When the participants were asked to rank them, the most important trends to the participants tended to fall in the Other and Technology categories (Fig. 3, right).

To illustrate the type of trends the participants contributed and their sustainability coding, three examples are presented in Table 1. The suggestion that nano-technology, for instance, will become more relevant in future making was regarded by the authors as

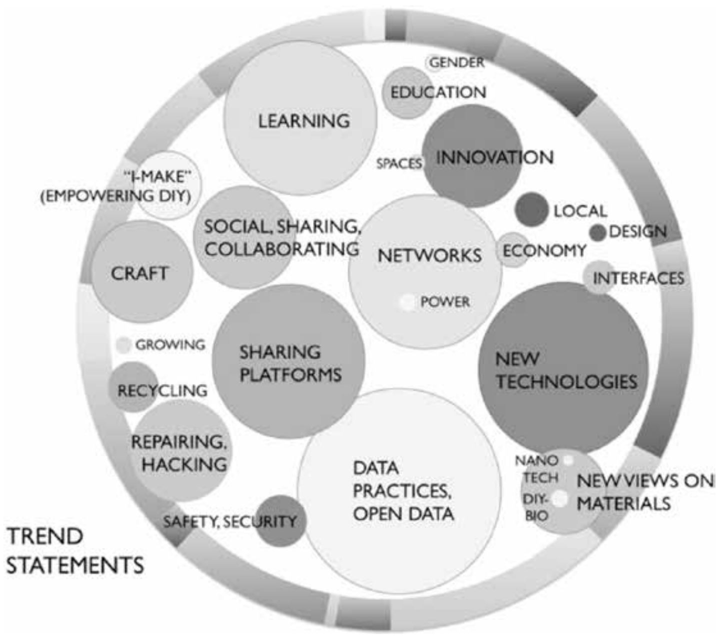

Fig. 2. Trend statement themes.

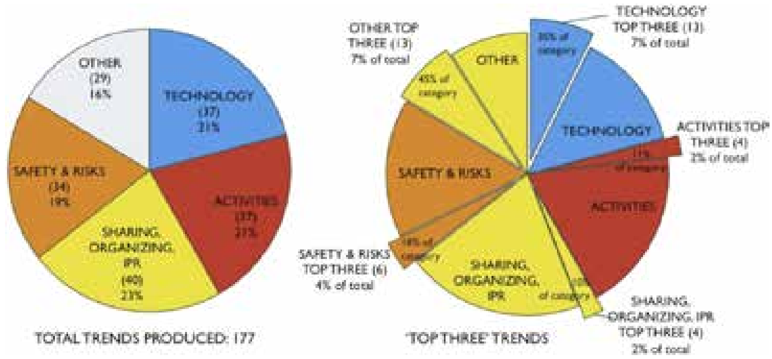

Fig. 3. Breakdown of trend categories.

having environmental implications, but none clearly expressed by the participants themselves.

Environmental implications related mainly to Technology trends, as seen in Fig. 4 (left). Participants directly expressed environmental concerns more in the Safety & Risks, Activities and Sharing/Organizing/IPR categories, while there were more unexpressed implications in the Technology category (Fig. 4, centre). Taken together, trends involving sustainability issues were in the clear minority: of the 177 trends produced, only 48 involved an environmental concern, whether expressed directly or not (Fig. 4, right).

4.2. Solutions

The afternoon's session yielded 262 solution proposals placed directly on the fab lab surfaces, indicating the exact location of the solution (Fig. 5), as well as on a "miscellaneous wall" created in the space. In total 37% of all solution proposals were posted on the miscellaneous wall, indicating that participants did not see future solutions for the library makerspace confined to the current fab lab environment.

The thematic clustering of solution proposals is illustrated in Fig. 6, showing wide variation in how specific the solutions were as well as the topics they addressed. The solutions' distribution among the pre-given categories differed from the trend distribution, as the "Other" category was used in 38% of the solutions and the second biggest category was Technology at 22% (Fig. 7, left). Between 1 and 4% of the solutions in each category had sustainability implications, the highest proportions being in the Other and Technology categories (Fig. 7, centre).

To ensure participants were not merely forgetting to express sustainability issues, they were asked to focus on sustainability solutions and implications for ten minutes at the end of the exercise, using the specific Sustainability post-it notes as well as "marking" existing solutions around the room for their sustainability relevance (Fig. 8). The results after this prompt are seen in Fig. 9, where Sustainability category solutions accounted for 8% of the total. As with the trends, overall the Technology category had the highest percentage of sustainability-relevant solution proposals (Fig. 9, centre).

The overall proportion of sustainability-relevant solutions compared to the total is comparable to the trend ratios, with 75% of solutions having no sustainability issues (Fig. 9, right). However, in comparison to trends, a notably larger ratio of these solutions expressed sustainability relevance directly, compared to those with environmental implications that were not expressed (both before and particularly after prompting). This indicates that practitioners may find it easier to identify implications for environmental sustainability when concretising solutions.

4.3. The sustainability faction

The workshop structure and subsequent analysis aimed especially at identifying whether environmental considerations

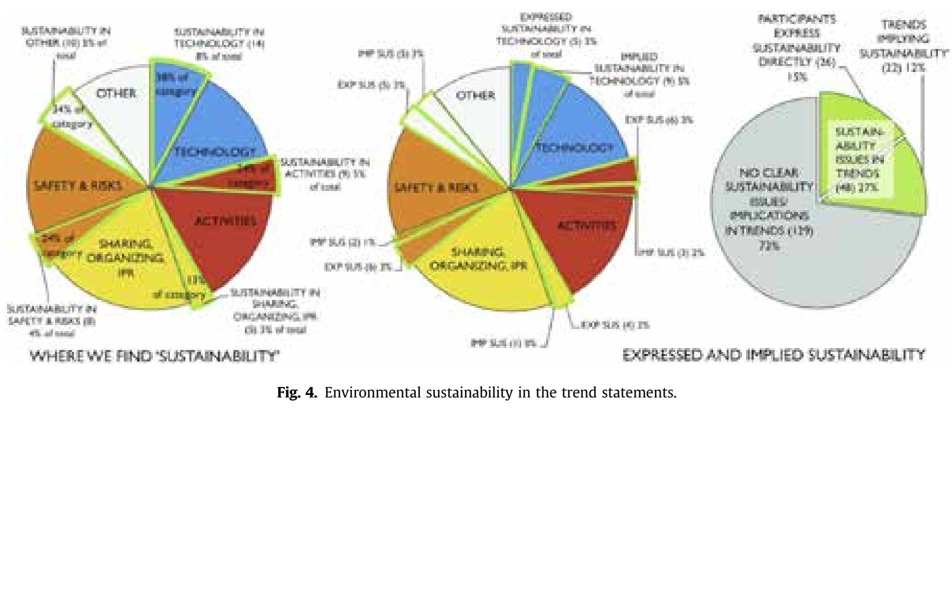

Fig. 4. Environmental sustainability in the trend statements.

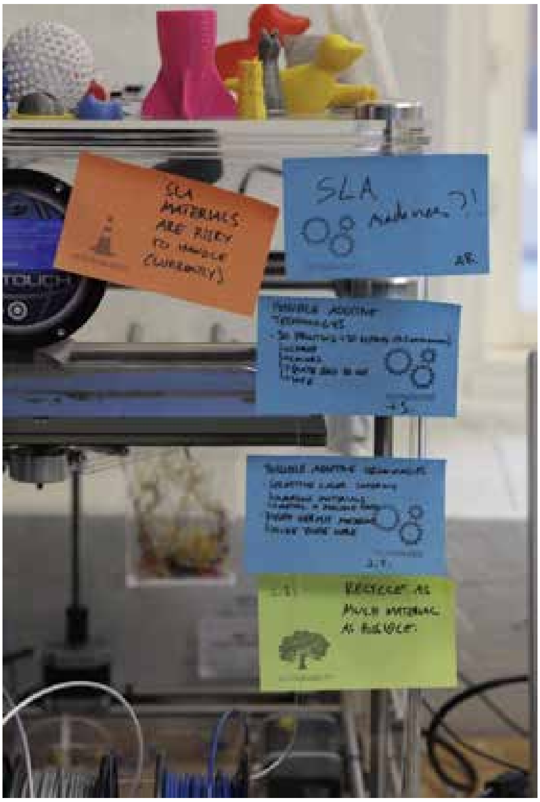

Fig. 5. Participant solution statements.

emerged naturally in the identification and expression of trends and concrete solutions. This allowed assessment of how salient or latent these issues may be for these practitioners, as well as what particular types of practitioners raise which issues. Three of the participants were known to be explicitly ecologically oriented in their own practice and self-identified environmental sustainability as a key concern for them in the introduction round of the workshop. These three participants formed a “sustainability faction”, who consistently raised sustainability-related concerns throughout the workshop. It thus became interesting to compare the proposals made by this group to the others.

Fig. 10 (left) illustrates where this group expressed environmental concerns directly in their trends and where the authors identified unexpressed environmental implications. This is compared against the other participants' sustainability-related trends. Unsurprisingly, the sustainability faction directly expressed sustainability concerns more often than the other participants (10% of the total, compared to the others' 5%), but the other participants still generated trends that have sustainability implications (11% of the total, compared to the sustainability group's 1%). The solutions differ, as the other participants expressed sustainability concerns in 11% of all solutions while the sustainability faction did so in 6%. This seems to imply a comfort the sustainability group felt with expressing their environmental concerns in general trends but less certainty when it came to actual solutions in a makerspace. This will be discussed further in the following sections.

5. Findings: property space analysis of trend and solution interrelations

Sustainable Consumption and Production research has long shown a high discrepancy between pro-environmental attitudes and actual behaviours: the “behaviour-attitude gap” (e.g. Kollmuss and Agyeman, 2002). The gap may stem from sustainability being a “good” that is evoked for reasons of self-identity, an inability to realise pro-environmental intentions within the structural constraints of current society, or sustainability forming an ideology that lacks concretisation in some areas (Shove et al., 2012).

The phenomenon is also likely to feature in how sustainability is represented in a given futures exercise. This potential discrepancy was taken into account in the design of the present experiment, by asking the participants to produce two qualitatively different ways to address future sustainability: through trends and through

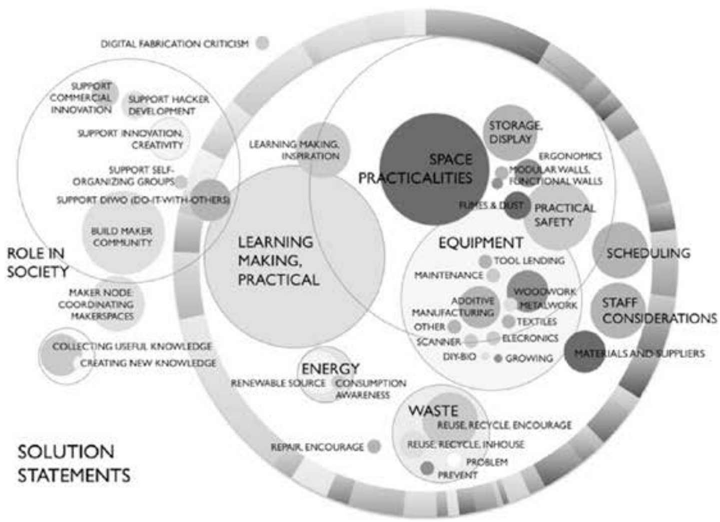

Fig. 6. Solution statement themes.

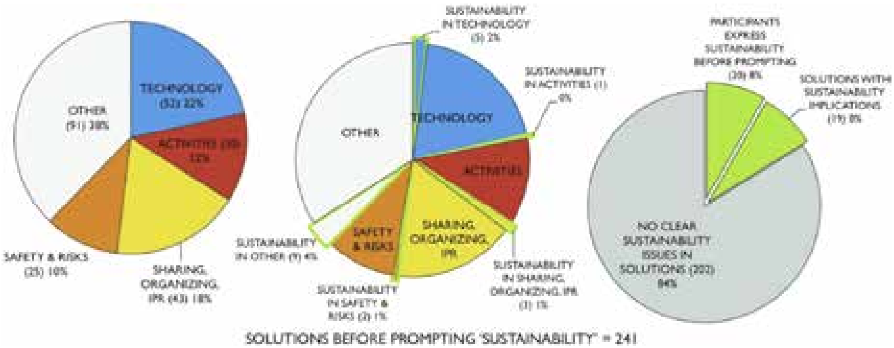

Fig. 7. Breakdown of solution proposals by category and environmental sustainability in each category (before the sustainability prompt).

concrete solutions. The pairing between the two should provide cues as to which trends find concretisation in solutions, or otherwise.

The analysis identified three types of relations to sustainability in the issues raised by participants: no relation, expressed sustainability implication, and clear unrecognised sustainability implication as judged by the researchers. These three categories form a logical property space (Becker, 1998; Rihoux and Ragin, 2009), exhibited in Table 2.[2]

This property space allows a closer examination of the issues raised as relevant for makerspaces in 2020 by making salient three types of comparisons. Firstly, there are the issues that have no clear sustainability relevance (in Table 3 in white): 326 items, or 72.9%. Thus, also as trend-solution pairs, the bulk of issues regarding future maker facilities and practices are in no clear way connected to environmental sustainability. Secondly, the paired issues that have some unrecognised sustainability implications ("implied") appear in light grey in Table 3: 37 items, or 8.3%. Thirdly, there are those future issues that the participants themselves expressed as relating to environmental sustainability (in Table 3 in dark grey): 84 items, or 18.8%. These latter proportions call for more detailed examination.

The main themes in each property space category are listed in Table 4. In the dark grey sections of the table, where participants were most active in identifying environmental issues, the largest clusters addressed material cycles, product and material longevity and energy. A noteworthy number of trend statements referred generically to recycling and reusing materials and repairing products. These matched with many solutions supporting these activities within a makerspace by lay citizens. Several repair-related trends also aimed to normatively mainstream repair through more significant cultural changes, whether by government policy, communications campaigns or formal education, but they could not be matched with any concrete solutions.

Many themes in the upper rows of the table pointed inward to personal fabrication itself. With these trend-solution pairs, the participants were less systematic in identifying environmental issues. Such issues included reused, easily updated and easily maintained equipment for makerspaces or the hacker ideology where even consumer products can be easily opened up, modified and customised, and repaired. Surprisingly, only one solution expressed concern about how the makerspace receives its materials: "*Logistics of supplies*" on a Sustainability post-it.

Some trends could not be matched with solutions but were nevertheless compelling for future consideration. One theme, for instance, addressed how current mass production will change: whether in altered supply chains or transformations in the production system itself. Another proposed that production will become localised and factories will move back into cities. This may indicate the emerging nature of a desired new paradigm where radical abstract transformations can be envisioned but not as yet the concrete steps to these visions.

There are thus differences (asymmetries) in how environmental sustainability was recognised and addressed in the trend-solution pairs. This is the reason to operate with the property space: not all items are equally comparable or even amenable to thematic clustering with regards to sustainability. The asymmetries in sustainability expression are likely to have resulted from difficulties to concretise some visionary trends or conversely connect practical solutions to larger trends. They may also be artefacts of the setting: participants may have failed to consider one or the other side thoroughly in the flurry of the workshop.

For this reason the next level in detailed analysis compares only the trend-solution pairs in "fully unrecognised sustainability implications" and "clear sustainability expression". This was done to

Fig. 8. Participants responded to the sustainability prompt by "tagging" others' post-its with pieces of a green Sustainability post-it.

[2] All the solution and trend expressions were also examined as possible false expressions of sustainability: "participants' false positives", where either solutions or trends claimed to have clear sustainability implication but are proven by research not to have one. No such statements were found. These categories were thus redacted out of the analysis (Rihoux and Ragin, 2009).

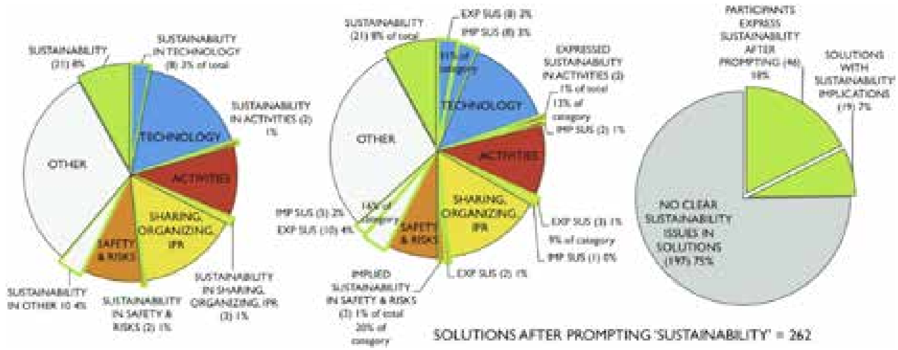

Fig. 9. Breakdown of solutions by category and sustainability in each category after the sustainability prompt.

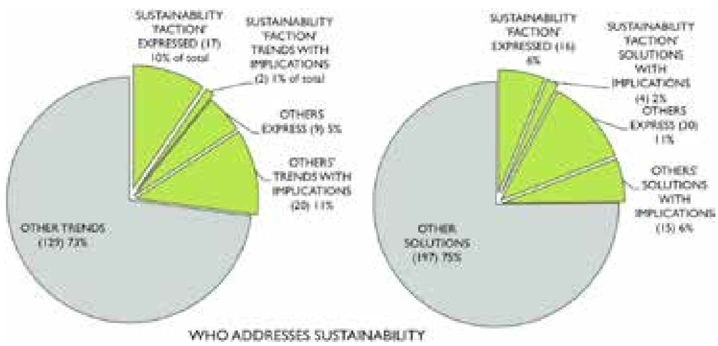

Fig. 10. Comparing the "sustainability faction" to the other participants.

identify if there were qualitative differences between these categories that are symmetric with respect to the interrelation between solutions and trends.

The trend-solution pairs in the Fully Unrecognised case indicated issues worth monitoring for future making, especially regarding technology development or combinations of elements enabled by new technologies such as disparate materials or embedded electronics. DIYbio is a novel and likely unfamiliar phenomenon, and it appears likely that participants ignored its sustainability implications. Another set of trend-solution pairs suggested growth of shared makerspaces, as opposed to digital fabrication at home. These solutions prompted more functional coordination among the spaces around the city and especially the role of a city library makerspace in this coordination. Finally, the issues of tool lending in a library makerspace and product design hospitable to hacking were not noted as having sustainability implications by the participants. They may simply have evaded participants' attention in the workshop and were easily passed over.

Table 2
Logical categories "property space" of interrelations between trends, solutions and whether sustainability is expressed or not expressed (implied).

Trends / Solutions	S0 = solutions with no sustainability expression or implication	S1 = solutions with no sustainability expression but clear sustainability implication	S2 = solutions with sustainability expression
T0 = Trends with no Sustainability expression or implication	T0S0 Issues with no clear sustainability relevance.	T0S1 Unrecognised sustainability solutions not connected to any sustainability trends.	T0S2 Expressed sustainability solutions that may have been difficult to trend.
T1 = Trends with no Sustainability expression but clear sustainability implication	T1S0 Unrecognised sustainability trends, not concretised by any sustainability solutions.	T1S1 Trends connected to solutions where both have clear sustainability implication not recognised by participants: Fully unrecognised sustainability implications.	T1S2 Trends with unrecognised sustainability implication, concretised by expressed sustainability solutions.
T2 = Trends with Sustainability expression	T2S0 Expressed sustainability trends that do not find any concretisation.	T2S1 Expressed sustainability trends concretised only by solutions with non-recognised sustainability implication.	T2S2 Clear sustainability expression.

Table 3
Pairing solutions and trends in the property space.

Trends \ Solutions	S0	S1 ("implied" sustainability solution)	S2 ("expressed" sustainability solution)
T0	**T0S0** 129 no sus. trends 197 no sus. solutions	**T0S1** 5 solutions not connected to trends.	**T0S2** 5 solutions not connected to trends.
T1 ("implied" sustainability trend)	**T1S0** 12 trends not connected to solutions.	**T1S1** 9 trends connected with 11 solutions.	**T1S2** 4 trends connected with 7 solutions.
T2 ("expressed" sustainability trend)	**T2S0** 7 trends not connected to solutions.	**T2S1** 3 trends connected with 5 solutions.	**T2S2** 18 trends connected with 35 solutions.

Nonetheless both had direct relevance for the set-up of the library maker facility.

The Clearly Expressed case pointed especially to issues of material eco-efficiency: reduce, reuse, recycle and repair. The trend-solution pairs addressed the personal level, i.e. waste reuse and product repair within the makerspace, as well as the municipal level, in particular the relationship between individual makers and existing recycling infrastructure in the spirit of a circular economy. Only a few solutions addressed *prevention* of waste from the outset, as preferable to reuse, an issue the authors had expected would be discussed more.

There were also a significant number of solutions dedicated to energy issues among the Clearly Expressed issues: the deployment of renewable energy sources, the desire to make electricity consumption more visible and other solutions to reduce overall energy consumption.[3] The environmental attributes (or dangers) of the materials themselves, beyond dust and fumes, were little addressed by the participants. An exception was the solution reading: "*hierarchy of good-bad materials on display (critical material thinking)*", which also alluded to the library's potential role in sustainability education.

The differences between the expressed and unrecognised became most apparent when the differences between issues the "sustainability faction" voiced and those voiced by the other ten participants were examined, as shown in Table 5. The proportions of the sustainability faction's contributions varied in the logical spaces that contain asymmetric trend-solution pairs, but their role becomes visible in the symmetric pairs of Fully Unrecognised and Clear Expression cases.

In the Clear Expression case, the sustainability faction seemed to be concerned with engaging the wider society in maker culture via repair activities, as well as engaging maker activists in "sustainability" via recycling infrastructures. The other participants showed more interest in the environmental issues in making activities themselves: dealing with the materials and the equipment, suggesting better fabbing processes and considering energy consumption. In waste prevention the sustainability group tended to focus on reuse, while the other participants offered solutions to combat waste and mistakes within the fabbing process itself, as well as pointing out the need for better (cleaner) materials in personal fabrication.

In the Fully Unrecognised case, the role of the sustainability faction was much smaller, contributing only two solutions (18% of solution proposals in the category) and no trends. This indicates the group was capable of identifying sustainability implications in trends and solutions that they themselves raised. This left a suite of trend-solution pairs raised by other participants with unrecognised environmental implications. These included DIYbio as well new equipment developments that may enable environmentally problematic products (where disassembly becomes more challenging, for instance). The two solutions raised by the sustainability group related to shared and common-pool resources, i.e. tool lending and sharing resources among city makerspaces.

The pro-environmental makers thus had limited engagement with unrecognised issues, and their engagement was also highly selective within this category: new materials and emerging technologies did not draw their attention. Also elsewhere in the trend-solution mapping space, trends with clear sustainability implications such as nano-technology, new material toxicity and changes in mass production were not addressed by the sustainability-oriented faction.

6. Discussion

The present study is part of the first line of research on how environmental sustainability is enacted in real-life personal fabrication settings. This line of research is important because the scientific evidence from which maker practitioners could draw remains scant, and much of the environmental impact of the potentially disruptive technologies rests on practitioners' shoulders.

To complement ethnographic research on present-day maker practices, the present study set-up was designed to assess how practitioners envision the future facilities and activities in this

[3] An "outlier" theme in the property space was represented in a trend-solution pair devoted to urban gardening or agriculture, arguing for its inclusion in making activities.

Table 4
Key themes in the property space.

Trends \ Solutions	S0	S1 ("implied" sustainability solution)	S2 ("expressed" sustainability solution)
T0	**Everything else** no sus trends no sus solutions	**Implied solution isolates** FLOSS[a] HANDICRAFT	**Difficult to trend** SPACE PLANNING OBSOLESCENCE SUPPLY CHAINS EXPERTISE
T1 ("implied" sustainability trend)	**Not recognised, not concretised trends** CHANGES TO MASS PRODUCTION LOCAL PRODUCTION NANO-TECH ALTERNATIVE ECONOMY	**Fully unrecognised** DIY-BIOLOGY LIBRARY TOOL LENDING SHARED MAKERSPACES NEW EQUIPMENT (TECHNOLOGIES)	**Expressed only in solution** OPEN EQUIPMENT SHARED CRAFTSPACES
T2 ("expressed" sustainability trend)	**Not concretised trends** BICYCLES REPAIR CULTURE ALTERNATIVE URBAN ALTERNATIVE CONSUMERISM	**Unrecognised expression** BIO-REGIONS TOXICITY	**Clear expression** URBAN AGRICULTURE REDUCTION IN ELECTRICITY CONSUMPTION RENEWABLE ENERGY SOURCES BETTER MATERIALS RECYCLE REPAIR REUSE WASTE REDUCE WASTE

[a]i.e. "free/libre/open source software".

rapidly moving field. The envisioning workshop for a real maker facility that will be set up in 2020 was used to avoid mere pro-environmental discourse without real-life anchoring. The participants, their peers and peer communities would be among the prime users and benefactors of this space. The study also provided indications of how maker practitioners address environmental issues when envisioning this future.

6.1. The workshop set-up and its validity for assessing practitioner views about future making

The workshop design allowed the authors to assess whether and which environmental sustainability issues would arise on their own accord, as well as whether and which issues would arise if environmental sustainability was brought in as a specific topic of attention. The participants worked on both trends and solutions for the year 2020, which further allowed the authors to centre on those issues that were consistently and symmetrically voiced both as trends and solutions. The set-up was thus geared in three ways to anchor participants to concrete practices and not their espoused views about environmental sustainability (Kollmuss and Agyeman, 2002; Shove et al., 2012).

The output of almost 500 trends and solutions indicates the practitioners faced no difficulty envisioning the future of making, even as they took the work seriously and worked carefully. There was good coverage of specific areas of making in both trends and solutions, and the participants also converged on several topics of mutual relevance to the different kinds of making in which they were involved. This was further ascertained through the prioritisation ("Top 3") exercises.

6.2. Participant perceptions of environmental sustainability of making in 2020

The majority of the expressed issues did not have a clear environmental implication. Environmental sustainability thus does not appear to be an overarching aspect of all or even the majority of issues the makers consider relevant in future makerspaces. This is in line

Table 5
Sustainability faction representation in trend-solution pairs.

Trends \ Solutions	S0	S1 ("implied" sustainability solution)	S2 ("expressed" sustainability solution)
T0	**Everything else** no sus trends no sus solutions	**Implied solution isolates** 0 trends. SF solutions 3/5 = 60%.	**Difficult to trend** 0 trends. SF solutions 0/5 = 0%.
T1 ("implied" sustainability solution)	**Difficult to trend** 0 trends. SF solutions 0/5 = 0%.	**Fully unrecognised** SF trends 0/9 = 0%. SF solutions 2/11 = 18%.	**Expressed only in solution** SF trends 0/4 = 0%. SF solutions 1/7 = 14%.
T2 ("expressed" sustainability trend)	**Not concretised trends** SF trends 5/7 = 71%. 0 solutions.	**Unrecognised expression** SF trends 1/3 = 33%. SF solutions 1/5 = 20%.	**Clear expression** SF trends 11/18 = 62%. SF solutions 14/35 = 40%.

with our ethnographic research on daily practices in setting up and running maker facilities (Kohtala, 2013; Kohtala and Bosqué, 2014).

The topics that participants expressed as relating to sustainability focused especially on repair, reducing, reusing and recycling of materials, electricity consumption and possibilities for more sustainable materials and energy. In these topics the sustainability-oriented faction was seen as playing a key role, proposing concrete solutions and trends, as well as expressing more contextual critique of digital fabrication. Particular proficiency was shown around topics of energy and recycling, where numerous normative "ought to" trends were also well concretised. The participants clearly operationalised what they found as the most pressing problems in making activities. In practice, recycling is beginning to be addressed in personal fabrication, but research on processes is dispersed and often experimental and art based (e.g. Baechler et al., 2013; Marchelli et al., 2011; Hakken, 2013). Additionally, the numerous participant suggestions to use solar and wind power resonate with published studies on the energy intensity of digital fabrication processes in comparison with mass production (e.g. Telenko and Seepersad, 2012; De Decker, 2014).

In contrast, trends with clear but unaddressed sustainability implications related mainly to emerging topics of making such as DIYbio, new materials such as nano based (Helland and Kastenholz, 2008), new technologies and the overall implications of distributed manufacturing displacing mass production. The toxicity of additive manufacturing materials was also weakly addressed by a single observation, even as this topic has been raised to the fore in research by Drizo and Pegna (2006) and Huang et al. (2013). A key dynamic was that the more technical and future-oriented issues were not at the focus of sustainability-oriented participants and the rest of the participants did not pay systematic attention to their potential environmental impacts.

7. Conclusions

The participants in this study were well able to envision the future of making, but they appeared to differ in their capacity to anticipate environmental issues: those competent and interested in assessing environmental impacts were different people from those competent and interested in keeping track of rapidly evolving new technologies and materials for making. This gap in practitioner orientation and competence is therefore potentially problematic.

Three obvious lines of implications and recommendations come forward. First, research objectives need to address these gaps in sustainability orientation and competence among makers. There is a clear need for targeted research on the environmental impacts of personal fabrication technologies and materials, as well as real-life maker practices. Availability of such research now could help mitigate or prevent negative impacts later, especially as the maker phenomenon becomes more widespread.

Secondly, dialogue should be fostered between and among maker subcultures. Interaction and communication between pro-environmental and new-technology-oriented practitioners can be enhanced through shared spaces, workshops and conferences.

Thirdly, guidance and solutions should be produced to better guide practitioners' everyday activities and the design of makerspaces. According to the current findings, maker practitioners are less likely to succeed in addressing environmental impacts on their own to the extent they espouse. On the other hand, precisely because makers like to represent themselves as environmentally benign, such practical, concrete guidance is more likely to be adopted, from manuals and checklists, to designs and solutions for equipment, better recycling systems and the like.

These conclusions may be generalised beyond the particular setting used in this study due to several contextual factors in how the envisioning workshop was set up. First, the group of practitioners in the workshop was chosen so that different maker subcultures were well represented and included environmentally-oriented maker groups. Each participant was proficient if not a leading practitioner in the Finnish context. Second, the Finnish context in the Helsinki region itself represents a middle ground in the competences of maker practitioners. It is not a global forerunner context such as the Netherlands or some regions of Italy, but personal fabrication activities are at roughly similar levels as in most Western capital regions. Third, the maker facility in the flagship Helsinki library presented a form of makerspace that was not fixed (in contrast to e.g. a fab lab), and library planners emphasised the flexibility in what their makerspace could become. The current findings are thus not confined to any particular type of maker facility or setting even as a public institution-run makerspace was the one that was being envisioned.

Currently, no evidence-based handbooks or manuals exist for how to conduct or organise environmentally-sound makerspaces or activities. Practitioners carry much of the burden for sustainability decision-making, based on scattered and not easily accessible research findings. Enhancing makers' competence in environmental issues through dialogue as well as practical solutions is paramount. Personal fabrication and its disruptive technologies present an important emerging study area for the cleaner production community.

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Paper 3

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The Story of MIT-Fablab Norway: Community Embedding of Peer Production

Cindy Kohtala and Camille Bosqué

Abstract:

MIT-Fablab Norway was one of the first Fab Labs ever established, in northern Norway in 2002. Despite this auspicious beginning to a network that is rapidly growing, surprisingly little has been written about the genesis of the network or the Fab Lab itself. We therefore aim to contribute to this knowledge gap with a narrative account of our independent ethnographic research visits to the Lab. We combine our researcher perspectives, which are informed by, on the one hand, Aesthetics and a phenomenological understanding and, on the other, Science and Technology Studies, with Design Research bridging both. Our account aims to richly describe the Lab's unique profile in the MIT Fab Lab network as a socially shaped entity and product of a particular time and place. Most salient in this narrative is the role of its charismatic founder, whose stories and metaphors become vehicles by which we come to understand how a Fab Lab forms its own identity, balancing the relationships with local stakeholders against those with the Fab Lab network; how it promotes certain principles and values of peer production; and how it represents itself to both maker insiders and outsiders. While situated and particular to this Lab, our interpretations may have implications for the trajectories of other Fab Labs and makerspaces, as well as our understanding of peer production as a new paradigm.

Keywords: Fab Lab, ethnography, MIT-Fablab Norway, material peer production

Cindy Kohtala and Camille Bosqué

1. INTRODUCTION

Material peer production ('fabbing' and 'making') is made possible to more and more citizens by the proliferation of shared makerspaces. Fab Labs have their own distinct network and identity, but they are often grouped together with makerspaces and hackerspaces in studies that examine making, whether conceptual or commercial. However, Fab Labs have the opportunity to share information, resources and projects globally within the Fab Lab network, which differentiates them from independent makerspaces. We focus on Fab Labs in this paper as we relate the story of one seminal Lab that was instrumental in the history of the Fab Lab network and remains an integral part of the network's mythology, MIT-Fablab Norway.

Fab Labs were established by Neil Gershenfeld and MIT's [1] Center for Bits and Atoms to "empower": to lead people around the world "to become technological protagonists rather than just spectators" (Gershenfeld 2005). As a network it is now rapidly growing and attracting increasing interest, from policymakers, educators and technology developers alike. The literature on Fab Labs, while relatively scant, tends to be informal: 'grey literature' reports and journalistic articles, on, for example, their role in education (e.g. Tiala 2011). In the English language, the number of surveys, overviews and analyses (e.g. Eychenne 2012, Bosqué and Ricard 2014, Menichinelli forthcoming) and academic studies is growing, with perspectives ranging from innovation (e.g. Troxler and Wolf 2010), to cultural and media studies (e.g. Walter-Herrmann and Büching 2013), to Human-Computer Interaction (e.g. Blikstein and Krannich 2013). The HCI field devotes increasing attention to digital fabrication, unsurprisingly, studying, for example, DIY online communities (e.g. Kuznetsov and Paulos 2010) and the activity of making (e.g. Tanenbaum et al. 2013) but seemingly less so the actual situated spaces, not to mention Fab Labs specifically. Seravalli (2012), for one, examines the social shaping of an independent makerspace.

Regarding individual Labs, Fablab Amsterdam has been the target of a user survey (Maldini 2013) and an ethnographic study (Ghalim 2013). Despite being one of the first Fab Labs to be established, little has been written about MIT-Fablab Norway, with the exception of Gjengedal (2006).

In spite of this emerging body of work, there remains a certain mystique that surrounds Fab Labs, their objectives and activities. Our aim in this paper is to disperse some of this mystique by allowing a Lab founder tell his own story. This in turn sheds light on how the Fab Lab network both shapes and is shaped by individual Labs (and their key players), and how maker ideologies and mythologies are formed, merge and diverge. Sections 3 to 6 thus set out the elements of our primary contribution: we illustrate how a Lab (and its founder) builds its own identity according to its perceived role and influence in the Fab Lab network; how it positions itself in its own local community and what that means for its identity as a makerspace; and how its identity as a non-conventional 'third' place is both threatened by traditional institutions and strengthened by its differentiation from them as it seeks to sustain itself. In all these elements storytelling is the pathway and metaphors the vehicle by which we come to know and understand them: how culture is transmitted and practices and values are promoted by a charismatic storyteller.

We summarise our analyses and interpretations in section 7 and spell out the implications, not only for current insight and future research potential, but for the future of Fab Labs themselves. The following section will review the methods for conducting the fieldwork and compiling this narrative.

2. METHODS

Our own story as researchers began independently, as we visited the Norwegian Lab separately, pursuing our own doctoral research and conducting our own fieldwork. In both cases Lab founder Haakon Karlsen Jr., a well-known personality in the network, hosted us and spoke extensively with us. We wrote about our experiences informally in weblogs, which we shared in our social media circles. Bosqué's account (in French) (Bosqué 2013) was similar to Kohtala's experience (Kohtala 2012a; 2012b) in a sufficiently compelling way that Kohtala translated Bosqué's text in another blog entry (Kohtala 2013); this led to an invitation by this Special Issue's editors to compile our accounts in a joint paper.

Our starting points were similar, as we both have design backgrounds and have been conducting ethnographic research in makerspaces. We both employed semi-structured interviews and recorded conversations and observations in fieldnotes. The interviews allowed the subject to dictate what he felt was important while certain topics were anchored according to our respective research interests – as true to ethnographic research tradition (e.g. Van Maanen 1988). The interview topics were hence not derived from literature or any theoretical background as an attempt to confirm theory. In Norway the Lab's profile regarding typical activities, users, relationships in the local community and ties with the global network were important to both of us, while Kohtala probed especially environmental sustainability issues and Bosqué investigated the very roots of MIT-Fablab Norway and thus the origins of the network itself.

Kohtala's data set consisted of nine audio and three video recordings, 200 photographs and fieldnotes. The videos and photographs were not analysed but served to supplement the fieldnotes; qualitative data analysis was conducted on the fieldnotes and audio transcriptions (according to Strauss and Corbin 1998). Bosqué's data consisted of eight hours of interview (in five audio recordings), 400 photographs, fieldnotes and numerous drawings made during conversations as a key research tool (Taussig 2011).

What was at first problematic from the perspective of ethnographic research (but something that emerged as a key finding) is that there was surprisingly little activity ongoing in the Lab during our visits that we could observe. Visitors came in and out and there was much coffee consumed, but it was not the type of traffic nor amount of fabricating activity we were accustomed to from other Fab Labs. During Kohtala's visit (four days in September-October 2012) there were regular visitors but only one person came in and used the equipment (for prototyping). During Bosqué's visit (ten days in June 2013) the fabrication tools were not used at all. This seeming inactivity found its explanation as we document below, but for data gathering these circumstances affected us differently.

For Kohtala, reporting on the visit necessitated heavy reliance on Karlsen's own speech and problematised useful comparisons between, for instance, what he and others said and what they actually did. This had to be taken into account in the data analysis: as the circumstances naturally led to examination of discourse and rhetoric, the categories or themes generated through axial coding (Strauss and Corbin 1998) deliberately contrasted ideology and value statements with (descriptions of) actions that instantiated these values. This resulted in the following themes:

• Fab Lab definitions and values (using Karlsen's own repeated rhetoric);

• practical descriptions (who does what; history and origins);

• what they do (current projects, comparable against what is espoused as valuable work);

• p2p as a new paradigm (understood through metaphors, what it is not, and what it may be, as compared to what they actually do);

• design (as a natural focus for a design researcher); and

• sustainability (as a central concern of her doctoral research).

For Bosqué, the mutual impact of ethnologist on study site in the process of developing an emic, insider view was an important methodological issue. The rather odd experience of immersion of a maker-researcher in a nearly empty Fab Lab site thereby became an important theme (following Favret-Saada 1990). Her other main topics included the history and pre-history of the Lab; the projects undertaken and promoted; and the description of the site and its current status.

We expanded upon these themes in writing independently and proceeded to interweave the texts, a conversation that involved ranking not only what was most salient (e.g. prevalent in the data) but what we regarded as most important for future theory building and further research. This resulted in three main themes; we illustrate how they are presented in the structure of this paper in terms of 'stories' in Figure 1.

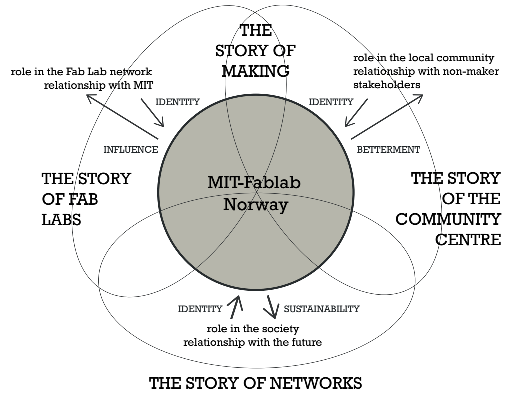

Figure 1: The themes of this narrative and how they are presented: the three themes (role in the Fab Lab network, role in the local community and role in society) are described via four stories, respectively the story of Fab Labs, the story of the community centre and the story of networks. The fourth story, the story of making, bridges the network and local community themes and each story is presented in a separate section, as follows.

3. THE STORY OF FAB LABS

3.1 The Birth of the Network

Surprising little has been written about the germination of the first Fab Labs aside from Gershenfeld's own account (2005). Both Bosqué and Kohtala listed this history as a theme and Bosqué especially pursued this line of inquiry (see Bosqué forthcoming). What became salient were not only the local details previously unpublished, which were themselves absorbing, but the multiple voices presenting alternative versions of the birth. This is obviously not unusual in itself, but it served to illustrate that how main characters choose to tell and share these stories, and with whom, reveals much about how they see their local conditions, what they esteem, and how they view their own rights to shared commons. Considering the history in this way is a tangible and logical starting point, as makerspaces often consider the decision to become an official Fab Lab or not upon inception. Each Lab will thereafter have its own relationship with MIT as well as with the rest of the network and can choose how this relationship is embedded in its identity and, in reverse, how it wants to affect the development of the network. (See Figure 1.) In turn, the MIT mothership can use individual Labs' stories and projects in the evolution of its own mythology, oft repeated in the popular press.

Enthusiasts of maker culture often meet Haakon Karlsen Jr. first (or solely) in Neil Gershenfeld's book Fab, where Gershenfeld uses the expression "growing inventors" to present "community leaders around the world, who are embracing emerging technology to help with the growth of not only the food and the business in their communities but also the people" (Gershenfeld 2005, 77). From personal fabrication to grassroots community development, "technological protagonists" such as Mel King in Boston, Nana Kyei in Ghana and Kalbag in India are described throughout the book as local inventors, raising opportunities through technologies for the people around them.

In the book's 'Network' chapter, Gershenfeld presents several examples of "innovators in telecommunications infrastructure" (Gershenfeld 2005, 181). Karlsen is one of them; two pages elaborate on how, despite the fact this farmer and herder in the Lyngen Alps is "less interested in hearing from satellites in space than from his animals in the mountains", one day he comes up with the idea of tracking his sheep with the help of radio signals (Gershenfeld 2005, 187). Karlsen is presented as a down-to-earth person with relatively prosaic interests: to simply find his animals in the mountains at the end of the summer and protect them from danger. With the help of Telenor's Tromsø office, Norway's national telecom operator, Karlsen developed a kind of GPS receiver that was quickly able to report locations. Bosqué took one sentence from Fab and asked Karlsen to give more details: "Telenor initially put these together, then in 2003 a Fab Lab opened on Haakon's farm to continue development and production of the radios and antennas there" (Gershenfeld 2005, 189). This prompt brought forth the story of the Electronic Shepherd, in which everything started a little before the year 2000.

According to Karlsen, at that time livestock populations were suffering due to rampant disease; in 1994 the Norwegian government established a laboratory for artificial insemination of sheep and goats. In the Lyngen region, however, Karlsen in collaboration with several farmers and shepherds were seeing surprising success rates of up to 94% instead of the usual 10%. Karlsen quickly realised this was due to two farmers he was working with, who knew their animals so well they knew how to inseminate at the exact moment of ovulation. "To succeed, it was necessary to know when the females were in heat. I suggested that we imagine for ourselves a technical tool to measure hormones," Karlsen recounted.

Eventually they developed a small temperature-sensing device that sent a message to warn the farmer that ovulation was impending, based on the female's brain activity. Later they thought about possible use for the device for the rest of the year: "We put an accelerometer in our little machine to capture the movements of the sheep. To test this feature, we created a system that calls home after fifteen minutes of inactivity for the sheep, saying, 'I'm dead'. We then put in a GPS, which allowed us to get the geographical coordinates of the sheep sent to the farmers." The original "sheep phone" – later called Electronic Shepherd – was born, in a "strange" laboratory on a farm on top of the world. In order to improve the GPS reception from the fells to the farms, Karlsen and his colleagues worked with Telenor for one year.

When the Center for Bits and Atoms won the National Science Foundation Grant in 2003, MIT engineers began to look for local communities around the world they could help via digital fabrication: "Instead of bringing information technology to the masses, the fab labs bring information technology development to the masses," explained Gershenfeld, in the official press release (NSF 2004). Karlsen had a more colourful version:

> There was an innovation competition launched by MIT globally to develop local projects. MIT sent some of its best teachers to Norway to find a suitable cooperation project. They found us through Telenor, who told them: 'There is this crazy guy lost in the fjord who devised sensors for his animals.' We enjoyed a great year of cooperation with MIT in 2001 and we were invited to Boston to present and develop this project.

When Bosqué asked about the very start of the Fab Lab, Karlsen immediately referred to "we":

> It was fantastic, but after years of collaboration we had to terminate the project. We had a discussion at MIT in Boston and we decided to do something to further enable this kind of adventure, something we would call… a Fab Lab. A Fabrication Laboratory. The decision was taken on 18 October 2002, I remember. We first decided to launch three Fab Labs. One in Pune with a man named Kalbag, from Vigyan Ashram, south of Mumbai, and another in a poor neighbourhood of Boston called South End Technology Center, with Mel King. And the third here in Norway.

In conversations with Kohtala, these three labs also formed the constellation of the first Labs in repeated tellings. At one point, Karlsen hesitated for a moment, remembering: "No, Ghana also came. And Costa Rica also has some story…." To be sure, this is confirmed in NSF's press release: "The first international fab lab was established in Cartago, Costa Rica, in July 2002 at the Costa Rica Institute of Technology. [...] This was followed in June 2003 by a fab lab far above the Arctic Circle in Solvik Gård near Tromsø, Norway" (NSF 2004).

Bosqué also asked Karlsen if he remembers when the words Fab Lab were spoken for the first time. He replied:

> In my memory there was Gershenfeld, Kalbag, Mel King and me. Mel King is an old fellow who was a professor at MIT and Kalbag was an old Indian who had many projects in the community. He came into contact with MIT through links with the Indian government. A bit like here, he had created a local system for watering different plantations and was spotted by MIT.

In the 'official' version, MIT-Fablab Norway is one (excellent) example among many others; in Karlsen's version, the team consists of the "growing inventors" that Gershenfeld presents in Fab, and he ensconces himself comfortably at the same table, at the centre of the story. Bosqué later interviewed Sherry Lassiter, Director of the Fab Foundation, a body that supports development of the network, who had another version: "How did it start in Norway? Well, I think at one point, after seeing what we did in Ghana and Costa Rica, Haakon must have come to us to ask if we could do the same at his place…." As is common in these kinds of endeavours, people remember, reason and portray the origin stories differently; what are highly relevant details for one are for others natural to present in a more sweeping manner. Our intention is not to establish for posterity whether MIT-Fablab Norway was number two or three or five in the world, but rather to emphasise the importance the MIT connection may carry for some Labs: in this case core to the Norwegian Lab's identity while peripheral to others'.

Bosqué for example also later interviewed Mel King, who expressed little interest in the Fab Lab movement, having visited only the Norway Lab in the early years ("There is a little bridge named after me there") – while remaining active in and committed to the Boston Lab. For Karlsen, in contrast, the close connection to MIT – and close friendship with Gershenfeld – both based on the Electronic Shepherd project, earned him and his projects a new identity as well as especial influence in the emerging network, particularly in the early years. In the following section we discuss this influence in the form of another Karlsen story: the definition of a Fab Lab.

3.2. What Fab Labs Should Be

A salient feature to Kohtala during her research visit was Karlsen's use of repetition in his storytelling, to punctuate and persuade, and the most common repeated phrase (all of which are italicised in this section) was his definition of a Fab Lab: *a global network of people who want to cooperate and share knowledge*. Fab Labs must also be *free and open*: one must not close the door to anyone nor have a "taxi metre" at the door. Fab Labs may charge for their services if needed, but they should do so "in a room beside". We should concentrate on what *people really need*, not on useless things. People need to solve their own problems, there *where they live*.

This last phrase is also stressed by Gershenfeld, in Fab, news articles and documentaries. Karlsen showed Kohtala a CNN-produced video on Gershenfeld and the Fab Lab concept, focusing especially on the Norway Lab. Gershenfeld speaks: "What we find is that people don't just need information on a screen, they need it out in the world *where they live* … for health care, for jobs, for education…" (CNN 2008; emphasis added). He reaffirms Karlsen's underscoring of the local and situated, or perhaps vice versa.

In fact Karlsen's and Gershenfeld's discourses diverge and converge like a DNA strand: they converge on concepts such as 'community', i.e. community empowerment and betterment, meeting needs, and *where they live*, but Karlsen plays down the role of the equipment. "The absolute most important success criteria for a Fab Lab [is] the people." 3D printers are especially useless – except when learning how to make them. In contrast, Gershenfeld defines Fab Labs as "high tech, low cost workshops, equipped with the tools to make almost everything…" (CNN 2008). It is possible that Karlsen, given the growing media interest in all things related to personal fabrication, feels increasing pressure (or responsibility) to put the people, not the technologies, at the centre of the story. We will even see this prioritisation physically, in the layout of the Norwegian Lab space, in section 4.

This is not a conflict but rather a sliding scale of choice: an opportunity for ongoing debate, not only for the Fab Lab network but for the entire maker movement. What Karlsen values in a Fab Lab and the relationship between the social and technological remain central points of discussion in maker discourse today (e.g. Bauwens et al. 2012). Principles of open access and sharing knowledge were explicitly embedded in the Fab Charter, a document that Fab Labs are strongly encouraged to display and one in whose development Karlsen played a role. As for what is done in Fab Labs and makerspaces, and why, this is an ongoing ethical debate in the network, as well as maker culture, in which Karlsen surely carries less sway despite his best efforts. We will later return to Karlsen's definition of a Fab Lab, as it becomes central to the question of the network's future as well as how we regard – or, rather, how Karlsen describes – our transition to a network society.

4. THE STORY OF THE COMMUNITY CENTRE

Alongside MIT-Fablab Norway's identity as a seminal MIT Fab Lab, the site's peripheral location is core to its identity. The Lab is reached by a small laneway leading off a pleasant road that winds its way south of the town of Lyngseidet through a landscape of fells and farms, far up north on the 69th parallel. It is a large, traditional Lapp log building that looks like a community centre or a rural dance hall. It is surrounded by smaller buildings for accommodation, where both researchers stayed. Its entrance is flanked by two flags: that of the region and an American flag. Each year about 600 people pass through the Lab's doors.

Inside, a community centre is indeed brought to mind, as the centre of the space is filled with chairs and tables set up as for meeting or dining, a video-conferencing system and a large fireplace. All technology is in the periphery: on the sides, along the walls. The open kitchen is important. Karlsen joked about it with Bosqué: "When Neil Gershenfeld of MIT came to see the finished chalet and saw the kitchen, he told me that it was useless, that I had made a mistake [...]! The result proved I was right. A Fab Lab is people, not just machines."

Gershenfeld apparently also exclaimed about the number of beds here and there, near workstations, where one can remove shoes and have a quick nap. Next to the kitchen, coffee, various teas, muesli, biscuits – and Aquavit – are available. The many tables (and outside cabins) help accommodate any visitors who want to stay in the area for a few days to go hiking or skiing. The Fab Lab is thus a tourist facility as well as a place for prototyping, a function that guarantees a good part of its funding. Karlsen even said that skiers sometimes become curious and use the Lab.

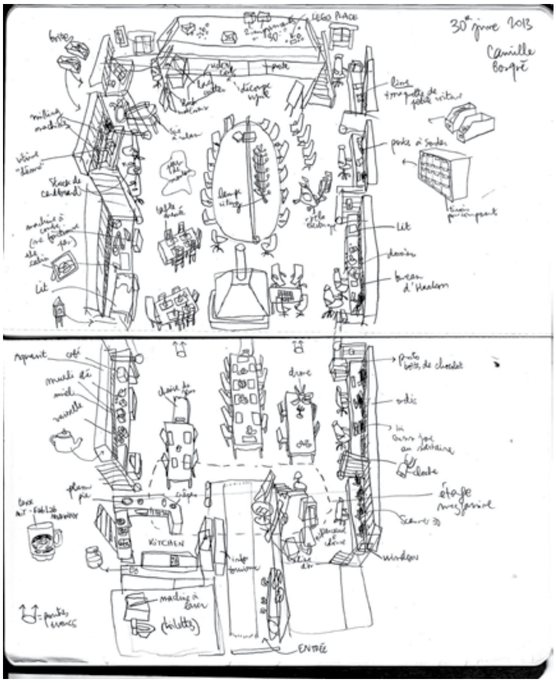

Figure 2: MIT-Fablab Norway, extract from Bosqué's sketchbook (30 June 2013). Note the placement of hearth, chairs and tables in the centre, while digital fabrication tools and equipment are centrifuged to the back and sides. There is a kitchen immediately to the left as one enters and a bed or resting place on each side among the workstations.

Karlsen is in his early sixties. He was born here and, after training as an engineer, spent his youth working with sheep insemination on the family farm, which is located "just down from the Fab Lab". He's an unmissable figure in the region; he has also been successively a teacher and farmer. He owns several houses and land at the edge of the fjord. Karlsen himself described his Fab Lab as now more of a "community centre" than a place for prototyping: "It has even held a wedding celebration!" His stories to both researchers about visitors, activities and projects confirmed this representation.

For instance, the video-conferencing screen broadcast other Fab Labs' webcams during our visits, but it is especially useful for other purposes: Karlsen reported how professionals such as nurses come here to attend distance education courses conducted in Oslo or Trondheim. The mayor of the municipality came by during Kohtala's visit; Karlsen said he drops in from time to time to discuss local problems, such as the number of school drop-outs in the region. Others popped in for coffee during Bosqué's visit to find out about the impending birth of the most recent foal.

Such unconventional activities for a Fab Lab also meant unconventional roles for researchers. We helped cook, we went for walks in the stunning terrain, and we worked long hours – either talking with Karlsen and his visitors or working alone on our notes, bathed in the strange pine-yellow light. The equipment was usually silent.

When we dined, we sat on dramatic high-backed wooden chairs, each named and physically profiled after a local fell. Designer Jens Dyvik (see DyvikDesign 2013) had helped realise the chairs on the ShopBot, a milling machine that was conspicuous by its absence. Bosqué began to ask about it often enough that finally – despite his reticence to have any focus at all on the technologies – Karlsen agreed to take her to the farm where the milling machine was housed. It was hidden behind a door in a small shed at the end of a cluttered barn; it was dusty and likely not recently or regularly used. Moreover access was difficult and the room narrow. During winter, when sheep come back from the fells, they are herded in with the ShopBot.

Perhaps because MIT-Fablab Norway was quite unlike any other fieldwork site we had visited, we became hyper-aware of how Fab Labs are 'third places' other than work or home. We saw afresh how the Fab Lab network – as a community as well as a collection of communities – differs from how we understand and relate to institutionalised societal structures such as formal education or industrial mass production. This can paint Labs as unfamiliar and mysterious places for the average citizen.

However, it was 'normal' for anyone to walk into the Norway Fab Lab, from the mayor to farmers to the neighbour renovating his house; this almost domestication of fabbing (especially considering the kitchen and the beds in the Lab) began to render the outside world and its conventional structures as almost unnatural in their turn. This was compounded by our own experiences of immersion and suspension in the Lab's environment, as well as Karlsen's own discourse – which heaped scorn on traditional institutions (especially universities during Kohtala's visit) while praising openness and reciprocity. Such a normalising process was obviously enabled by Karlsen's charisma and role in his community; we have no doubt he would have had an equally influential role in Lyngen had the MIT connection and Fab Lab germination not occurred. As it did, Karlsen was the conduit to make the otherwise opaque construct of a Fab Lab acceptable and everyday in its small, rural local community.

To be fair, considering the population of the region, perhaps the amount of personal fabrication that took place during our visits was proportional, and there was certainly evidence in abundance. In the following section we return to the core of a Fab Lab, the making, a subject that bridges the identities of the Norwegian Fab Lab as both a pioneering MIT Lab and as a third place for community work of various kinds. What should be noted about the Lab's making activity is its place in the timeline: the most significant hustle and bustle seems to have passed, as the Lab continues in a trajectory into more consequential municipal community involvement, likely driven by funding opportunities as well as Karlsen's commitment to local action and betterment. However, even as Karlsen relied on storytelling means to communicate the tale of the community centre, an obvious source of pride and achievement, he was especially animated when relating stories about making and inventing.

5. THE STORY OF MAKING

In his anecdotes Karlsen was especially skilled at building up tension: at 'gearing up' his listener for an exciting outcome. "What is this?" he asked Kohtala, as they sat at the table on a chilly September evening, hints of the Northern Lights glimmering outside. The stories always started this way, the presentation of the problem or context, the heroes, the first ideas and prototypes, the struggles… and eventually the result, whether it was the artificial insemination device, developed as part of the Electronic Shepherd process, or a solar-powered LED lamp developed in Africa. The effect was not to emphasise the object or the invention however; the intention was always to stress the need the invention caters to – which was always local, always developed in collaboration, and always something that combined previous, even ancient, ideas in new ways.

Bosqué asked directly for an inventory of the projects and was treated to the same storytelling ritual. "What is this?" The first object Karlsen put on the table was a cardboard box and many small plastic pieces, presented as prototypes for chocolates. "One day, in 2007, a woman came to the door and said: I want to make a chocolate factory, I need some chocolate moulds. And we said: OK, no problem, we can make it, we can help you. So we started to make moulds."

"What is this? It's a house for a dog race." The next object was placed on the table, as simply sheets of lasercut cardboard. The organisers of a large dog race had come to Karlsen and explained their problem: they had hundreds of dogs racing over an entire fortnight and sleeping in hay outside. A proper shelter system was needed so each dog could have security and rest. "I said we can do it flat-packed," explained Karlsen, "and we made the first prototypes." In story after story links were constantly drawn between people and ideas, during planning and fabrication. When Bosqué asked Karlsen why he likes these stories, he answered: "You must not have the feeling that I have made that alone; all this is the result of a global network of people who want to cooperate and share knowledge: two kids from Boston, a shy woman from northern Norway…." Who had the idea, who did the design, who contributed – sometimes these were remembered and important and sometimes not. What was central was that the outcome and the process in which it was developed manifested the spirit of a Fab Lab: free and open, for people's own needs, where they live.

Moreover, knowledge should be shared and people should not be categorised when they come in the door: "inventor" became synonymous with "designer" and "maker". In Nordic languages, the word 'design' is cognate with the term 'form-giving' and many other words equally serve, such as 'planning' or 'developing'. Karlsen tended to favour these other verbs, and during a pause Kohtala asked him directly for his definition of design. He hesitated and laughed at the same time: "No.…" "Because these [objects you are showing me] are designed," she countered. "So all the boats, all things people have needed over millions of years, have been developed by people where they are, [...] for their use, scaled for the way they really need it," he replied. The real answer to Kohtala's question came at the end of the day, at the end of a different, unrelated story: "Back to your answer, what is design, and who has the decision on what is design, *nobody*," he stated emphatically. One cannot help but be reminded that Lyngseidet is a small, remote municipality where urban tendencies to specialisation are impossible or even detrimental. Making and fabbing in this context serve as local entrepreneur support and citizen education, for purposes ranging from marketing and product development to agriculture or telecommunications research to simply exploring and learning.

The making and prototyping was furthermore where the links to the global network became more visible: during Kohtala's visit Knut Klo was working on the design of a drone, a 'helicopter' that could carry a camera, whose plans were to be made available to the Fab Lab community on the Wiki. The drone had first been developed by Klo, Karlsen and Dyvik, who by that point was in Indonesia working on the inter-lab "low-cost prosthesis project" with Fablab Amsterdam's Alex Schaub (lowcostprosthesis.org 2012). In the early hectic years, the Norway Fab Lab was a making hub, hosting several well-attended Boot Camps as well as FAB2.5 and forming important, lasting connections. In one video (fablabbcn 2009) posted on YouTube, Gershenfeld can be seen perched on the mezzanine, working with his computer on his stomach. Schaub is also there, as is Tomas Diez from Fab Lab Barcelona.

Karlsen spoke less about these Boot Camps, however; his stories tended to regale the early projects that marked the genesis of a particular Lab, whether it was the "sheep phone" that inaugurated his own Lab or the LED lamp (which became known as the "Haakon lamp") associated with the genesis of one of the Kenyan Labs, which Karlsen helped found. Similarly, Karlsen's making stories about solutions for the region's entrepreneurs emphasised local needs and the connection to and collaboration with the local community. In all probability stories strictly about fabbing activities amongst maker insiders had less appeal except when they had a social dimension. To be sure, what excited Karlsen most was diversity: when anyone can design, develop, invent, make and build, and when diverse people come together without the barriers of conventional institutions, then something truly powerful can happen.

6. THE STORY OF NETWORKS

In Karlsen's world, such an empowering vision is rendered conceivable and attainable by the three processes we have observed thus far: the third place characteristic of Fab Labs, which helps break down traditional conceptions of access and jurisdiction; the normalising effect of the Norway Lab and how it embraces a wider set of collaborators not restricted to maker practitioners; and the promotion of the vision through rhetoric which aims to inculcate attitudes and values. We learn through his storytelling that entering the Fab Lab world promises skills and knowledge, a way to meet one's own needs and other espoused benefits; we may thus consider not just desirable but inevitable the transition to a network-based society – or the non-hierarchical, non-judgmental society Karlsen wishes to promote.

For example, for all his criticisms of universities – in Kohtala's paraphrasing this meant their hierarchies and the power granted to professors, their ability to dominate innovation support systems as well as knowledge transmission, and their tyranny over science – Karlsen would provide numerous inspiring stories about individuals reaching their own potential: where people of all ages and abilities were granted access to knowledge sharing and teaching at the Fab Lab. Moreover, where the "magic" happened was not merely through open access for the marginalised but when different types of people were able to mix together: "During many years we have had so many strange people here in the Lab; [...] when you find many different people, where they have this cross-over, then you have something. How can you put all this down in rules: it's impossible." For Karlsen, "strange" was a neutral adjective used to describe nearly everything, from the unconventional or surprising to the unknown. These strange people are not allowed into universities because of "rules" – which also bar them from jobs, entrepreneurial support or simply opportunities to explore their own ideas and inventions.

This does not mean a network-oriented, heterarchical social world does not have rules: the Fab Lab network has the Fab Charter that embodies the values of openness, access and reciprocity. There are no sanctions for not following the Charter, if one does not include having to endure Karlsen's heated chastisements. Instead, in true p2p fashion, the conformity ranking is made transparent: an ongoing chart that documents each Lab's compliance with the Charter principles – open access for the public, having a basic inventory of the same equipment that eases inter-lab project work, and giving something back to the network (NMÍ Kvikan 2012).

Nevertheless, for Karlsen rules are like categories: they protect people, which serves to keep some in and others out. And it is not only the people who should not be categorised – the Fab Lab should not and cannot be. In the first years the 'network' existed, those first few Labs scattered among various continents, Karlsen said the Americans did not know how to take it: was it a development project, an aid project or an innovation project? On research projects and surveys that try to make sense of the current network, Karlsen scoffed:

> …there are so many people who see that the Fab Lab network is super cool, and they try to make a description, to put the Fab Lab into a form, into a matrix, and it never fits. The Fab Lab here is one thing, the Fab Lab in Africa is another, the Fab Lab in the United States is a third one. There is no sense to make all the labs exactly the same. The diversity, that's the good thing with the Fab Lab.

Such diversity allows each Lab to cater to local needs, where people live. But does this not problematise 'normal' support one could influence or access, such as government innovation policy and funding? "That's a super problem for all the Labs. We don't fit into any policy; [...] they don't know how to handle us. When they put us in the state budget, yes or no, we are there, we are not that."

However, if indeed the Fab Lab world does become normalised (and note that we use both normalisation and domestication as descriptive, exploratory terms and not as definitive interpretations at this point), what may happen to its self-conception as an alternative: as *not* institutionalised or at least consciously avoiding the hierarchic structures of mainstream institutions and their concomitant rules and categories? Perhaps there are some clues in how Karlsen understands and conveys the very idea of the Fab Lab network.

Let us examine a diagram, a typical organisation chart with boxes and rows. Karlsen explains:

> Normally an organisation should be like this: you have the Fab Foundation at the top, you have Fab Labs, you have business creation here in the middle, and you have the Academy here on the side. This is the normal way to organise a structure. [...] This is how you would learn it in [...] business school. Then you report, and everything works well. But here, in the Fab Lab structure, all the arrows are upside down. [...] The top is only a result of what is happening in the grassroots. It's not some people who sit at the top and give orders and make the structure down through the organisation, down to the Labs growing up all around the world. Here you seed something and coming up is a strange thing, and you have [...] the grassroots stream up all the time, so all the arrows in a Fab Lab organisation are upside down. Or downside up.

How Karlsen describes the process of "seeding" here is particularly apt: one may plant a seed, but what comes up will take on its own character based on the soil, the sun and the nutrients available. The best way to develop, or grow, solutions for a particular community is to enable it to meet its own local needs, where people live. A Fab Lab is a seed, or a container for one.

And what then is the role of the Fab Lab network? For Karlsen, the network is a global coming together of "many small brains" that become a "big brain" when they cooperate and work together according to the same values or "with the same approach". When describing the 'helicopter' project, Karlsen suddenly veered to talking about the material chosen for the propellers and how their milled birch propellers do not break. Superior to the carbon fibre common in such projects, birch is described as "fantastic", a "living material" that has "computers in every cell". This way of portraying wood – and plants by implication – as a distribution of intelligence is so akin to how he describes the Fab Lab network, i.e. as a "network of brains", that one sits up and takes notice. This is why Karlsen wants us to focus on the people and not on the technologies: it is the people and their individual strengths and curiosities that have formed the Fab Lab movement and will continue its trajectory.

Again we hear the definition of a Fab Lab: "A house like this, that's only a facility and all the things you have around here, the tools, software, a Fab Lab you have to remember absolutely all the time, a Fab Lab is a global network of people. It's not a global network of houses or other dead things, it's a global network of people that want to cooperate and share knowledge." Not only the material is living; the knowledge is living knowledge and the network is alive and organic, growing, evolving and changing. Technologies in themselves do not better communities; the "remarkable story" is contained within the "combination of brains who push all of us a little bit forward". Karlsen asks us to consider "how did all these brains stimulate each other to make remarkable things, and you [will] see that nothing is impossible". Through Karlsen's storytelling, people become the heroes of a collective adventure, where doing one's best and doing it for everyone's betterment is paramount.

Nevertheless, there is an obvious concern for an organisation that wants to remain free and open. Near the end of the visit, Kohtala asked about a Boot Camp schedule where a discussion topic was titled "Business, Entrepreneurship and Sustainability". Despite common rhetoric in maker culture as to the environmental benefits of small-scale digital fabrication, Karlsen confirmed that "sustainability" in that case was financial, not environmental, as funding for Fab Labs becomes increasingly problematic as they develop beyond the first few years. Economic sustainability must now be the priority for Labs: it is "the most important thing". How this is playing out in the Norwegian Lab, however, seems to indicate a move away from making and fabbing as central practices and towards other sources of income such as tourism that require completely different skill sets.

Moreover, emphasising the Fab Lab as a third space may recruit maker practitioners, but it may also repel other key stakeholders. Karlsen's stories are peppered with references to how Fab Labs fall into the gaps – neither concerned with education, innovation, agriculture, industry, technology development nor social development – but all of these and none of them simultaneously. In a world of old paradigm conventional structures, funders may find it difficult to grasp what exactly it is they are being asked to finance. The very identity of a Fab Lab as representing a new paradigm, as expressed in Karlsen's discourse, is both the source of its frailty and its strength.

7. DISCUSSION AND CONCLUSION

For reasons of space, clarity and coherence, we have summarised our fieldwork into three themes and four stories, keeping in mind the perils of omission that come with such neat packaging. We have attempted to limit these dangers by constricting the size of our themes and restricting our analysis to focus on Karlsen's storytelling. This allows us to condense the following key messages.

Not all Fab Labs in the MIT Fab Lab network are alike, despite their surface similarity; each Lab becomes an entity shaped by – and over time also shaping – its founders, funders, fabbers and followers. Labs are also likely to experience a tension or need for balance between acting in their particular local environment and reaping the benefits of belonging to the network. Labs may value the MIT connection and wish to make it part of their profile and in turn may procure more influence in the network; MIT's Center for Bits and Atoms by the same token can co-opt positive stories from individual Labs. Because of both its history in the network and its peripheral location, both of which tend to the extreme, the Norway Lab accentuates this Janus-faced character: its Arctic rurality is core to its identity, but so is the identity of MIT and the global, virtual network. We thereby clearly see the role that seminal Fab Labs and individuals may play in communicating (and at times steering) the image, goals, strategies, visions and ambitions of the Fab Lab network – both within the network itself as well as to outsiders.

Secondly, we have shown how the Norwegian Fab Lab, in its identity as community centre, differs from other Labs in the network in a way that makes it more acceptable and almost domesticated to its local community. This made for a somewhat strange experience for the maker-researchers but is likely a factor of its peripheral location, which necessitates cooperation across a broad range of interests. Nevertheless, the effect was that of a distancing from prototyping and fabbing.

Thirdly, this portrait of a Fab Lab seemingly moving away from digital fabrication activities can indicate what may happen to younger labs as they become more established, swayed as they are by local conditions, charismatic leaders, and the need to remain funded in some form. The last point is especially pertinent, as the need to ensure economic sustainability easily comes into conflict with other values espoused in makerspaces: open access, free sharing, suspicion of mass manufacturing, and the like. This seems to be the fulcrum of success upon which Labs pivot – whether continued existence is ensured by becoming a community centre, a research laboratory, a fabrication service, or another adopted identity that conforms better to rather than rebels against conventional categories.

Finally, we have illustrated the role of stories and rhetoric in shaping culture – stories to boost learning, stories to establish reputation, and stories and metaphors on growing and seeding as guides for envisioning new forms of organisation. We have seen how this Fab Lab founder, with seemingly few exceptions, walks the talk and embeds the values he espouses in his Lab, but he may be afforded this opportunity by his other identities in the community (farmer, teacher, inventor, social worker and so on) that surround his profile of Fab Lab Director.

We emphasise that these implications emerge from a particular story created by a place, time, a charismatic lead character, and a particular set of circumstances. Capturing a moment of time in an otherwise quickly changing phenomenon can shed light on what came before and – for the researchers that come after us – what develops in future. We find this particularly relevant in the case of Fab Labs, as they serve as a visible, observable representation of what happens when a group of people decide to formalise material peer production in terms of a designated space and provide a certain infrastructure for making.

Subsequent explorations may address the literature and reflect upon certain nuances of this story: exploring the data anew with lenses focused even more on how the community provides infrastructure and shares and protects its commons (as in Star and Ruhleder 1996; Ostrom 1990). This narrative aims to provide a foundation for this future work.

ENDNOTES

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Paper 4

Kohtala, C.
Making ‘Making’ Critical: How Sustainability is Constituted in Fab Lab Ideology.

Unpublished, in review.

MAKING 'MAKING' CRITICAL: HOW SUSTAINABILITY IS CONSTITUTED IN FAB LAB IDEOLOGY

ABSTRACT

Fab Labs, fabrication laboratories, are shared workshops where citizens can access digital fabrication equipment to design and make their own objects. They are proliferating rapidly and represent an alternative to mass production and consumption, an ideology whose environmental and social benefits their 'makers' like to espouse. If these practices spread, 'making' could become part of a shift towards more distributed 'prosumption' with less negative environmental impact. However, this would require that makers are enacting their values, an assumption that must be carefully examined ethnographically. This paper reports on a longitudinal ethnographic study in a university-based Fab Lab in northern Europe. The study revealed a gap between what Fab Lab actors espoused and what they practiced, especially with regards to promoting local production. There were opportunities for more sustainable practices in how this Fab Lab endorsed Open Design and making as 'Digital Craft'. However, these pro-environmental aspects would have to be made more visible and explicit if they are to become embedded in both espoused ideology and everyday routines in Fab Labs.

Keywords

Fab Lab, digital fabrication, open design, distributed production, sustainability

INTRODUCTION

Fab Labs, makerspaces and hackerspaces are varieties of shared workshops for personal fabrication activities, where people use digital fabrication equipment such as laser cutters and 3D printers to create their own artefacts. Production becomes an integral part of the consumption process in such activities, and personal fabrication or 'making' is thereby often termed 'prosumption' (Ritzer and Jurgenson, 2010). It is also often social and collaborative, entailing sharing and modifying of designs online, cooperation on projects and/or shared use of equipment in communal spaces, and is thus also known as 'commons-based peer production' (Benkler, 2006).

Of these communal spaces, hackerspace members (Maxigas, 2012) tend to focus on electronics and physical computing projects. Makerspaces are independent workshops in all forms, from commercial services to hands-on learning environments in museums and libraries. Fab Labs are workshops listed in MIT's Center for Bits & Atoms Fab Lab Program,[1] an organic and largely self-organizing international network whose members are strongly encouraged to comply with and publicly display the Fab Charter,[2] to acquire a common inventory of equipment[3] to facilitate cross-lab projects and to allow open access to the public. Fab

1 www.fablabs.io (accessed 25 March 2015).
2 www.fabfoundation.org/fab-labs/the-fab-charter/ (accessed 25 March 2015).
3 www.fablabs.io/machines (accessed 23 April 2015).

Labs therefore have many elements in common, but each Lab is also free to determine its own identity, target user group, form of revenue, activities and stakeholders depending on its own local conditions. There were about 150 Labs worldwide in November 2012 (Maldini, 2013), 300 in June 2014[4] and over 480 by March 2015.[5] Because Fab Labs are the most organized makerspaces with the clearest identity, they are the target of the current study.

The rapid rise of makerspaces is only one aspect of digital fabrication to be reckoned with, along with the spread of 3D printing and other fabrication services online[6] and on the high street. It is therefore advisable that research begin to pay closer attention to the environmental issues that may accrue along with this momentum, as the potential to do away with negative impacts associated with mass production and distribution (and decouple them from socio-economic prosperity) is as great as the potential that new, unforeseen environmental consequences will arise and spread. Fab Labs regard themselves as offering a better alternative to mass production, by offering 'democratic', 'widespread access to the means for invention' (Gershenfeld, 2005: 42), but how this ideology is actually enacted throughout the rapidly growing network has been little studied as yet. Moreover, how environmental and social sustainability benefits may be embedded in these new prosumption patterns has not been articulated, despite the central role energy and materials play in such activities.

The research question in this article seeks to examine *how environmental and social sustainability is constituted in the making of a Fab Lab*. In other words, when physically and conceptually building a Fab Lab, do social groups articulate sustainability concerns? How do they enact these concerns?

FAB LABS

Currently, research on Fab Labs is beginning to emerge but remains scant. The seminal reference is Fab Lab founder Gershenfeld's own account (2005), as well as a volume of essays on Open Design collated by a group associated with Dutch Fab Labs (van Abel et al., 2011). These were joined by a volume from cultural and media studies (Walter-Herrmann and Büching, 2013) and a Special Issue of the *Journal of Peer Production* (Maxigas and Troxler, 2014). The Human-Computer Interaction field also features many studies on personal fabrication (e.g. Mota, 2011).

While there is little empirical work conducted on environmental issues in making (Kohtala, 2015; see also De Decker, 2014), there are nascent agendas to connect it to principles of a circular economy (e.g. Charter and Keiller, 2014) and to study the potential of such 'grassroots innovation' to contribute to building a more sustainable society (e.g. Smith et al., 2013). Personal fabrication is also woven into broader studies on citizen activism and socio-technological change, and this line of inquiry into 'Critical Making' (Ratto, 2011; Hertz, 2012a; Ratto and Boler, 2014) directly informs this study. Critical Making will be discussed further in a later section.

4 http://wiki.fablab.is/wiki/Portal:Labs (accessed 25 June 2014).

5 www.fablabs.io/labs (accessed 25 March 2015).

6 In Shapeways alone, an online marketplace for 3D printed products, the number of shops selling 3D designs (many run by design entrepreneurs) increased from 13 500 in 2013 to 23 000 in 2014 (Hagel et al., 2014; Mansee, 2014).

STUDYING 'SUSTAINABILITY'

There are many ways to investigate sustainability issues, and research *on* the actual environmental impacts of digital fabrication is needed (such as toxicity and life cycle impacts), but it cannot stand alone. Makers and stakeholders in Fab Labs need access to this knowledge, and they need ways to be able to translate it into something relevant and actionable in their own world (Kohtala and Hyysalo, 2015). This requires wider (and deeper) knowledge of what actually goes on in the social life of a Fab Lab and how actors build meaning and ideology together.

There are also many ways to examine how individuals and groups identify and pursue their ideals of a sustainable society. In conventional Sustainable Consumption and Production (SCP) research, the aim has often been to capture in empirical terms the behaviour-attitude gap: the difference between what 'consumers' espouse and what they actually purchase or do (e.g. Kollmuss and Agyeman, 2002). The objective is to identify leverage points for encouraging more pro-environmental behaviours (DEFRA, 2008). A problem nevertheless arises in the difficulty to agree on how an attitude can be defined and measured. Neither is 'making' reducible to a particular attitude-behaviour set: it is rather a combination of an individual's interactions with things, technologies, components and materials; interactions with other people; and even interactions with herself, in learning, acquiring skills and deciding what to pursue, how and why (Clarke and Star, 2003). It thus bears affinities to understanding action as a set of practices that involve both human and non-human elements (Shove et al., 2012), rather than 'behaviour' as such.

To complicate it further, 'making' is not a readily understood practice or set of practices either; it is not an everyday routine such as driving, showering or preparing meals. People come into making from different directions, from other social arenas, and involve themselves in co-creating the group life within a Fab Lab. Social groups shape, and are shaped by, technologies such as open source 3D printers or Arduino microcontroller boards. The technologies' symbolic meanings are constantly negotiated, as can be seen by the various public discourses on 3D printing: as a socio-economic opportunity for entrepreneurs, to a danger to people (e.g. guns), to a threat to an activity or community (e.g. crafts). Their creation and use are also often a reaction to something else, a way to counter some perceived inequalities or injustices, such as access to means of production or to STEM (science, technology, engineering, mathematics) education. Fab Labs and makerspaces are thereby alternative spaces: in Pfaffenberger's terms (1992) they can be seen as 'countercontexts' that are created specifically for the alternative activity that is 'making'. Countercontexts will be discussed further in a later section.

As an analytical framework, the approach of symbolic interactionism (Blumer, 1969) provides one way to navigate these challenges: to assess and interpret how a countercontext is constructed, how group life is conducted and how ideology is built – all within the flow of the everyday. Studying a site such as a Fab Lab is therefore a place where design 'happens', as a performance of interactions between people and materials: where objects being designed are technologies and material artefacts, but also concepts and constructs (Blumer, 1969: 10-12). How social worlds intersect, orbit or impinge is an important part of this analysis (Strauss, 1978: 122-123). In Fab Labs, these activities are set within a particular context, an alternative, harbouring space that nevertheless cannot protect the group or practices from external constraints and the entropy of routinization. The objective of the current study was therefore to foreground how sustainability 'happens' in this performance: to demonstrate the relationship between discourse and practice.

DATA AND METHODS

The focus of this longitudinal ethnography was a young Fab Lab in a university, a university being a typical, representative context for a Fab Lab. The author entered the situation when the Fab Lab was beginning to be constructed and the equipment was beginning to arrive. Direct observations and fieldnotes therefore began at that point, and information on events and decisions before this period was solicited in interviews and by reviewing online archival materials (public video and photo collections, news posts and the like) and several internal documents. Follow-up interviews were conducted with most key individuals thereafter (once or twice a year). The author visited the site most frequently during the building period, with less frequency in the subsequent two years (an average of once a month). This accumulated almost 80 sets of fieldnotes, twenty interviews (and numerous more informal conversations), almost 1300 photographs and more than 120 video recordings. The author also visited 13 Fab Labs in Europe and interviewed key actors in the Fab Lab network. This last dataset is not fully incorporated in this study, i.e. analysed for cross-comparison purposes here, but the general themes of fieldnotes and interviews have been taken into account in considering different contexts and how implications of this study may be generalized.

The data was analysed using open coding and key themes identified as arising from the data itself (not from any external theory or framework) (Strauss and Corbin, 1998). Themes were noted according to what was often seen and heard in the data, what subjects themselves reported as important and what topics or situations provoked strong reactions such as arguments or expressed joy. According to the research question, attention was paid to when subjects themselves raised topics relevant to sustainability[7] or acted accordingly and when the author herself had to prompt the topic. In deeper analysis, the relationships among the actors and their social worlds, among the concepts they held dear (and their opposites) and among the meanings they attached to objects (tangible and intangible) were mapped in diagrams (Clarke, 2005) and written out in memos, vignettes (Miles and Huberman, 1994: 81) and narrative summaries. A long compiled narrative was produced, structured chronologically and describing the Lab's trajectory (Strauss, 1993: 47-72; Bowker and Star, 1999; Johnson et al., 2010) according to the 'biography of technologies and practices' approach in science and technology studies (STS) (Pollock and Williams, 2008; Hyysalo, 2010), especially to highlight the important role of processes (Strauss, 1978: 126). The narratives and memos were shared and discussed with a mentor. The compiled narrative, upon which this paper is based, was shared with the research subjects for respondent validation.

7 i.e. topics deemed relevant based on literature as well as the author's extensive background in Design-for-Sustainability

FAB LAB BACKGROUND

The roots of the studied Fab Lab reach back to a 2007 university merger, during which a proposal was made to form platforms for innovative, multidisciplinary research and teaching, where academia, companies and the public sector could meet, develop new ideas, and design and prototype products. The platform opted by the design school focused on research and production in media and was prescribed its own public premises in 2011. While Media unit staff members had discussed for several years whether they would establish an electronics workshop for media department students, once the space was found, the idea of founding the country's first official MIT-associated Fab Lab grew in appeal. The unit's identity as platform for multidisciplinary dialogue to create 'societal impact' was clearly compatible with the diversity of users encouraged in a Fab Lab via open access to fabrication technologies, enabling people to solve their own local needs (Gershenfeld, 2005).

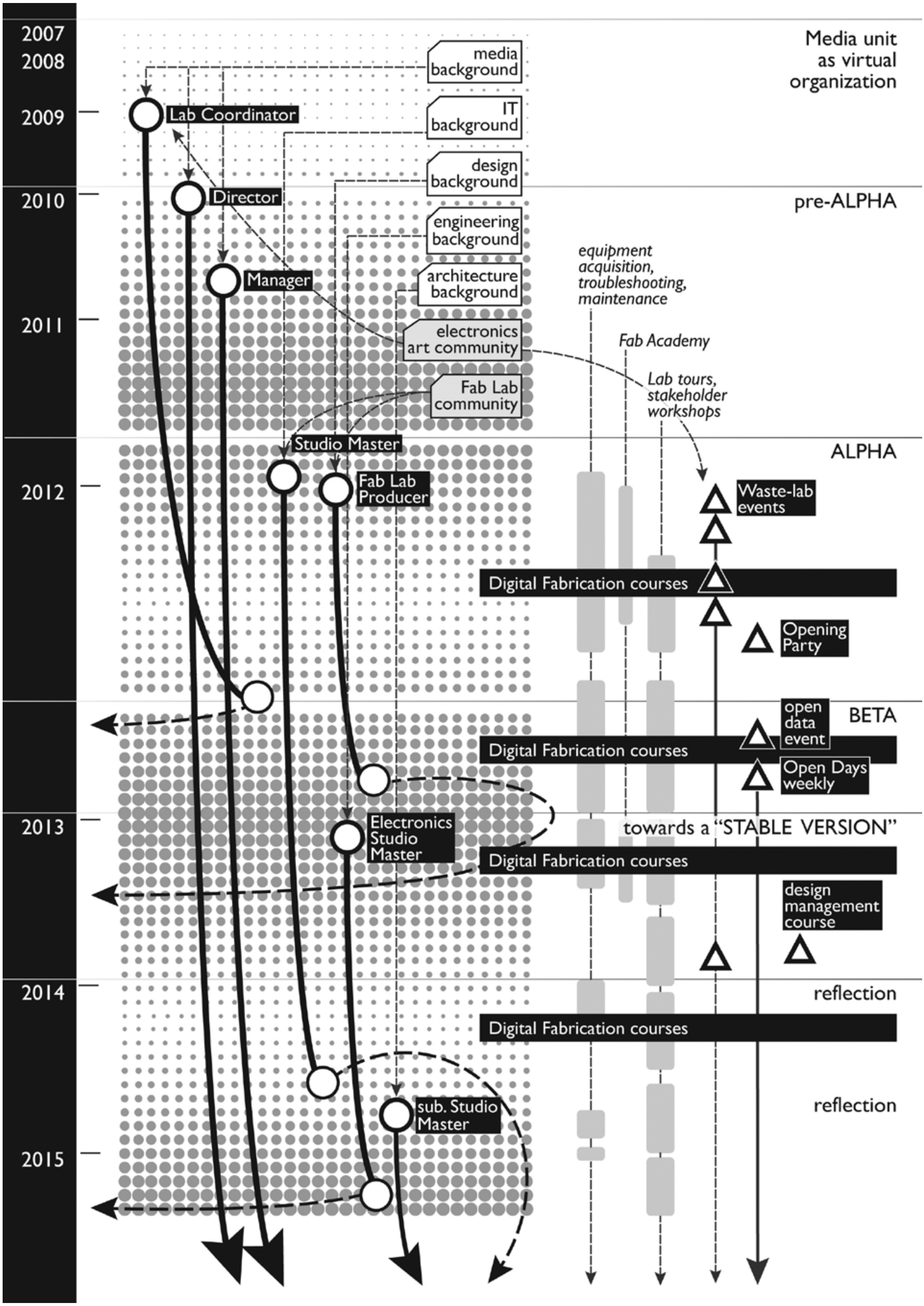
The process of building the Lab began in 2011 and operations began in earnest in spring 2012. (See Figure 1.) By the following year, organizers were describing the Lab and its operations as a 'stable version'. In keeping with this software development metaphor, the set-up phases could be termed 'Alpha' and 'Beta', hectic phases in which all actors had had to complete a myriad of tasks in a relatively short time period. The Media unit deemed it time to reflect on and reassess the Fab Lab's purpose and direction: it was important to support students' work, but the ideology of multidisciplinary dialogue and collaboration could not be neglected. Changes in staff over the years as well as cuts in funding affected how new strategies and directions could be implemented, especially given the sheer busyness of the Lab through all its phases. Changes or additions in equipment were also key influencing factors, which altered the layout of the lab and the demands on the organizers.

FIGURE 1: A simplified overview of the Fab Lab's development, indicating key phases, people (circles), activities (bars) and events (triangles). People's educational and work backgrounds as well as other communal involvements (other 'worlds') influenced their decisions and actions in the Fab Lab world. The actors came together to produce and offer events, akin to performances, while other activities became routine tasks. The ideology of the Fab Lab is thus represented in both the events and the routines, and sustainability concerns within this ideology thus arise or are notably absent in the Lab's interactions with stakeholders, in material and equipment acquisition and in what individuals brought to or took away from the Lab's social world.

Currently, funding and the Fab Lab's future physical location remain uncertain. The formerly separate multidisciplinary platforms (numbering now four) may be merged, including the Media unit, and the Fab Lab may be seen as a redundant facility if it is regarded as merely digital fabrication equipment that can be found elsewhere.

BUILDING IDEOLOGY THROUGH INTERACTION

The concept of the Fab Lab was built during the 'pre-alpha' phase, where the main actors sought to create a space for experimentation and multidisciplinary interchange. Especially



2007
2008
2009
2010
2011
2012
2013
2014
2015
Media unit as virtual organization
pre-ALPHA
ALPHA
BETA
towards a "STABLE VERSION"
reflection
reflection
media background
IT background
design background
engineering background
architecture background
electronics art community
Fab Lab community
Lab Coordinator
Director
Manager
Studio Master
Fab Lab Producer
Electronics Studio Master
sub. Studio Master
equipment acquisition, troubleshooting, maintenance
Fab Academy
Lab tours, stakeholder workshops
Waste-lab events
Opening Party
open data event
Open Days weekly
design management course
Digital Fabrication courses
Digital Fabrication courses
Digital Fabrication courses
Digital Fabrication courses

the unit's 'Lab Coordinator' sought to bring two communities together using the Open Days as the platform: the city's maker subcultures, including hacklab members and local experimental electronics art groups, and the art and design students. The makers would benefit from exposure to 'the theoretical knowledge and ... the design and artistic concepts and thinking' of the university, which they lacked, in his view, while the maker community would bring the electronics skills the students lacked as well as 'street credibility' and a maker 'aura of doing stuff'. Moreover, the sharing and peer learning ethos of Fab Labs could differentiate the Media unit as the foremost platform for Open Design and 'openness' in the university.

In the Fab Lab's later phases, the two main actors, the Studio Master and Fab Lab Producer, promoted the philosophy and practice of Open Design and openness particularly when conducting Digital Fabrication courses for the students: documenting and sharing one's work, modifying others' shared work to suit one's own purposes and collaborating on projects by contributing one's own skills and expertise using open source protocols. They also emphasized how personal fabrication was neither craft nor industrial manufacturing: it was a relationship between digital design and material realization, a dialogue between the 'bit and the atom'. Designing for such a context, which they termed 'Digital Craft', required a particular design sensitivity, something especially the Fab Lab Producer felt was under-addressed in the Fab Lab network world. 'Fab Labs come from a STEM culture, science, technology, engineering and math. So there's no design, even though there should be,' he explained, as the only actor in the Media unit coming from an industrial design background.[8] These aspects of the Fab Lab's ideology, how the actors saw the meanings of their actions, are illustrated in Figure 2.

In the Alpha phase, the opportunity to work with the first outside test users, the makers desired by the Lab Coordinator to precipitate a 'maker aura', came in the form of a Media-unit-funded project called Waste-Lab.[9] Two of the outside experimental artist-hacker groups collaborated with university researchers on the project, which aimed to explore artistic, ethical and practical perspectives on e-waste, repair, obsolescence and over-consumption. Local makers, hackers, electronics artists, designers as well as recycling experts were to gather and initiate a collaborative project, using the Fab Lab facilities if and where needed. The Studio Master was especially keen to participate and facilitate, having worked with waste issues in the past. One of the artists nevertheless warned the project coordinator that many of the most experimental artists would not come if the events were held in the ivory tower of the university. From the outset, the problems and challenges were laid out. The artist-hackers pointed out how they work: with post-consumer waste, which required much storage space, transport as well as slow building processes. One of them complained: 'This is a new area for us, to think about how to *design* a machine.' The project coordinator summarized: 'Oh, they're very critical of it [the Fab Lab]. It depends on the pragmatics of how you work. If ... you just use what you've got, what you've got lying around and what you find in flea markets, ...then that's the starting point. If you decide, well, I need

8 The Producer and the Studio Master were also the only staff members who had worked with, for and in Fab Labs previously.

9 the name has been changed

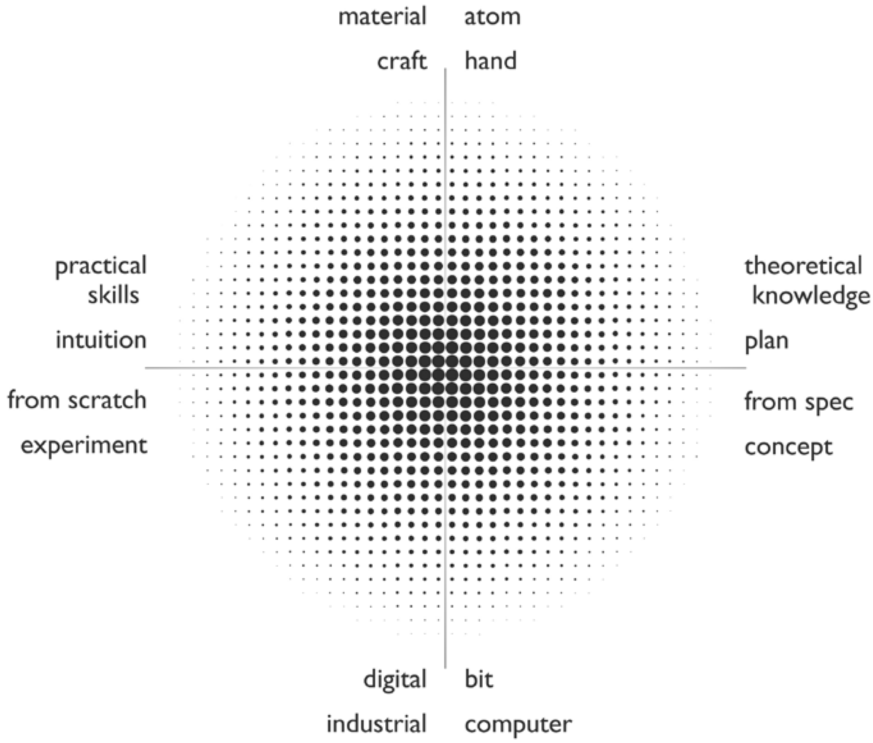


FIGURE 2: Concepts of importance to the actors in this study: a Fab Lab in a design school and design/designing in a Fab Lab entails a rich dialogue among these four elements. The practical skills and ability to experiment and use one’s intuition from maker culture would combine with the theoretical and conceptual skills learned in art and design formal education; the students would come to understand the interplay between the bit and the atom. All words and concepts as antitheses are taken directly from the data.

this to go with this thing I have, then ... Fab Lab could be the bridge between the fixing or the additional bit you need, or the customization of things. But I knew the conflict was there from the beginning, so it was like, is there any way you can compromise? Are there any spaces of compromise?’

In Figure 2, the Waste-lab group would have stood firmly on the left side of the diagram: working in an experimental, ad hoc, bricolage manner using materials they had to hand. The other side of the diagram represented working as ‘design’ and from ‘a design’. It also represented the institution and the university, which was bound by rules and stood for the elite and the exclusive. A Fab Lab may in principle promote inclusivity and open access, but this maker sub-culture could or would not engage with this Fab Lab, in this design school.

To demonstrate further how the Fab Lab was socially shaped, it is useful to see how certain concepts, i.e. 'objects' (Blumer, 1969), travelled through the development process, how their meanings were co-constructed and how or if their ideological content was visible in everyday practices over time. Four objects as key inputs and outputs will be elaborated, as best illustrating how especially socio-environmental concerns were manifest or neglected in the ideology building: from the material point of view 'equipment' and 'waste', and from the conceptual and ideological point of view 'meanings' and 'contexts'.

EQUIPMENT

The symbolic interactionist framework becomes particularly useful when one examines the activities around procuring equipment and materials. The technologies come to represent interactions and processes, intersections with another social worlds, subworlds and/or 'universes of discourse' (Strauss, 1978: 123). The decision to purchase an Ultimaker, for instance, was voiced by the actors as related to interpersonal connections: the Studio Master knew the company founders personally, as well as the product itself and how to use it, while the unit Manager did not know the equipment but met the company founders at an event. The Ultimaker was ordered even if it was problematic in the university's procurement regime. Moreover as an example of open hardware, it was nearly always pointed out to visitors as the open source 3D printer in the Lab.

In contrast, other equipment and materials were chosen precisely because of the ease of ordering. Casting materials, for instance, were readily available from MIT's U.S.-based inventory and less available from a European supplier. Components were ordered in discussion with someone in another multidisciplinary unit on another campus, because he had the contacts to order electronic components directly from China. Wood (plywood and MDF) was ordered in cooperation with the wood workshop in the design school. For both equipment and materials, local suppliers were indeed explicitly stated as preferable, but the preference was voiced in terms of ease of ordering in the university system as well as access to technical support if needed, and not in support of any local economy model or distributed production principle.

The ideology of open source, hardware and software, is also handled inconsistently in Fab Labs, with some prioritizing it with an almost religious zeal and others as a matter of convenience. In this Fab Lab, for instance, the large CNC milling machine was procured because there was a clear need for a larger fabrication machine in a design school, but also in part to become 'a real Fab Lab' (as the last piece of official Fab Lab inventory to be acquired). The meaning of the CNC machine is thus best understood as arising from the interactions between the decision-makers with the (proximal) student users on one hand and the (remote) Fab Lab network on the other. Before this CNC machine arrived, a group of delegates from an international open data event built a relatively large, open source CNC mill in the Fab Lab. Subsequently the machine was little if ever operated, and it has remained unused on the top shelf in the storage room. As an ideology, open hardware is admittedly less important in Fab Labs than open access, but open access is also compromised in this case: the current large CNC mill is so difficult to use that the Fab Lab Studio Masters are its main operators.

WASTE

A consistent finding encountered in the main research site but also in many other Fab Labs was how Fab Lab managers face a constant conflict between implementing visions and dealing with the everyday and the mundane. This issue is salient in the material waste issue in the studied Lab. The Waste-lab project could have been the obvious stakeholder with whom to tackle this very visible environmental (and practical) issue, with the Studio Master as a key ally, but they were both thwarted by the need to establish their own procedures. The Studio Master needed to build the Lab's 'hardware' and 'software' (as she called the physical infrastructure and operating procedures, respectively), to prepare for users' arrival, while the Waste-lab group could not congeal around a particular project. Nor did many group members deem the Fab Lab a space of value, and their activities continued in later years in other venues than the Fab Lab, particularly promoting product repair and material reuse explorations.

Over the years the Studio Masters were occasionally able to squeeze in time to fabricate a temporary solution, but these were not durable. Eventually the stand-in Studio Master[10] and the Electronics Studio Master managed to prioritize the task, and their more solid storage box beside the laser cutter meant that users were taking off-cut pieces first before going to the storage room to take a fresh, uncut piece of sheet material. The changing state of laser cutter and milling machine waste storage is illustrated in Figure 3.

10 who replaced the Studio Master temporarily when she went on study leave

THE MEANING OF MAKING: 'THE QUESTION IS, WHY?'

The title of this section derives from a telling moment in one of the videos recorded during the first Digital Fabrication Studio course. A group of three students are sitting at the table discussing what project they would like to create. One of the students has printed out a two-dimensional graphic pattern on an A4 sheet that he liked; he is trying to explain how they could turn it into a tangible fabbed object. Perhaps the graphic layers are layers of laser cut material assembled together. Perhaps this could make an interesting lamp, or a complex, interlocked puzzle. The student beside him says in a faux-dramatic way, leaning forward: 'The question is, *why*?' He laughs and quickly adds: 'But it's cool.'

This thereafter became the author's code for every moment where people wanted to question *what* people chose to fabricate in Fab Labs. A student in the first Digital Fabrication course, a member of the only group explicitly using reclaimed materials for their projects, explained her perspective: '[W]e are making something new that maybe we don't even need. We were also making jewellery and objects we don't need that much, so it was nicer to use recycled, reused materials, so we were not wasting resources or materials for things that are just for fun.' Eventually, the Media unit's discourse and strategy discussions would return to the need to be more than just a 'print service': to promote not only projects that were 'personally meaningful' to users (as in Lassiter, 2013: 251), but also to focus more on community building and addressing 'unmet local needs' (as in Gershenfeld, 2012) – both visions explicit in Fab Lab network ideology.


15.10.2012


7.11.2012


29.11.2012


29.11.2012


24.4.2013

19.3.2014


19.3.2014


10.10.2014

FIGURE 3: The ad hoc, design-on-the-run way of dealing with sheet off-cuts despite the obvious inconvenience as well as occasional rhetoric espousing concern with waste. Piled-up sheets of material blocked the laser cutter room's sliding door; were packed into crates, trolleys or cardboard boxes; or were stacked into fabricated stands that were not long lasting. The final solution of the plywood box kept the stacks neat and easy to access.

THE CONTEXT OF MAKING: THE NEW INDUSTRIAL REVOLUTION

During the course of the current research, both the ethnographic inquiry and the examination of the literature, it became apparent that while material and energy flows and impacts were the most obvious environmental issues in Fab Labs, it was more complex than that. Actors (in the main research site, but also in many other Fab Labs) did not necessarily see themselves as *un*-sustainable. They were part of a new and better movement. Making was more than just a hobby – it was part of a New Industrial Revolution, beyond the circumscriptions of mass production: networked, distributed and enabling people's full potential. As an ideological object, this vision stood for more than simply what people should do in Fab Labs, the meaning of making, but what society Fab Labs were making: the new context they were supposedly representing.

However, concerns were emerging in the Fab Lab network and among its observers and critics that this vision was not being actualized. The Special Issue of the *Journal of Peer Production* (Maxigas and Troxler, 2014) published editorials, some of which questioned the role of Fab Labs. Are Fab Labs there merely to forward the agenda of the existing capitalist and consumerist system, with its large multinational stakeholders belying the democratized, open access to small, non-proprietary, decentralized tools for production being espoused? Author Bruce Sterling admonished the global community at the FAB10 conference: 'Look behind this beautiful façade. Don't be naïve; go beyond your hobby frame of mind.' A Fab Lab manager from a Lab in north-central Europe attending FAB10 was inspired by Sterling's words and gratified to hear Gershenfeld speak: for him, it was 'good to know where Fab Lab was coming from, ...what his [Gershenfeld's] main idea was, because somewhere along the way quite a few Fab Labs are focusing on toy[s], and 3D printing, and Arduinos, and I really like the bigger picture, about this economic industrial revolution.' He, and many other FAB10 delegates, were awed by the beauty and vision of Barcelona's Valldaura Self-Sufficient Lab, where explorations on sustainable solutions for a city, as part of the city's 'metabolism', involve digital fabrication but also permaculture and experiments with bio-based materials. 'It's not about laser cutting baby cars, it's about using the laser cutter to produce things that matter, that have function, that have a reason to be built,' the Manager said about Valldaura.

In the Fab Lab studied, to become more than a 'print service' or a place to merely 'print toy ducks', the need arose to enforce the vision of a multidisciplinary, open, experimental platform. Making the vision explicit and visible, how the Fab Lab philosophy was a valued asset in the university, became more and more connected to survival, as funding sources became increasingly precarious. The Lab's workshops and activities had expressly aimed at this vision, by providing an alternative way to identify and meet local stakeholder needs, but this aim was either inconsistently successful or less visible to all observers.[11] Indications began to appear in the Lab's latter phases on how the vision could explicitly be connected to a more sustainability-oriented ideology. Unprompted by any questions about environmental sustainability, the stand-in Studio Master voiced his ambition to practically and creatively deal with the Fab Lab's waste outputs. Ideas for user clubs or projects included building a 3D printer from e-waste, exploring hydroponics and melting and reforming plastic waste. At the time of writing a filament extruder for recycling 3D printer plastic waste had been purchased.

The Fab Lab Producer regularly pointed out that personal fabrication is a local activity with the *potential* to reduce impacts from transport, while admitting that currently fabbing materials and components do usually travel long distances. At the beginning of every Digital Fabrication Studio course, he would point the students to resources such as Sourcemap[12] to urge them to pursue knowledge on supply chains and raw material sources. 'It's very pragmatic,' he said about Fab Labs: '"We have a problem, how do we solve it. Let's have a look." ... So I think it's going to succeed because if you come to these people and say you have to change the supply chain or do [something] another way, they will say, ok, let's try it.'

However, to ensure more rigorous attention to socio-environmental issues, one must also note how the strategy of the Waste-lab group was not successful. Its members were unable or unwilling to engage in the Lab as a 'space of compromise' or a platform for the kind of engaged critical making described by Ratto and his colleagues (Ratto and Boler, 2014; Hertz, 2012a). Whether as dialogue or room, the group did not enter the space represented in Figure 2. The Producer, in contrast, saw the dialogue represented in Figure 2 as the precise platform upon which sustainability discourse and practices can be fostered. 'I think the maker movement has a lot of influence in the way people perceive work, projects and the way of thinking, because you start from absolute reasoning; you start with what is at hand ... and you see what is possible. And what is changing for me personally, now that I've been more involved in making things..., is that you really start with what's *possible*, instead of what would be *ideal*. You understand much more what is possible and how to make it physical, so it's a different perspective. That can also come in when it comes to understanding all the problems of the *system*. If you expose people to "do your own car, do your own chair", then they will understand [what] it takes.'

A vision was thus being formed on what this Fab Lab was for, what role it would play in preparing for the New Industrial Revolution: a space not for mere reproduction or rote learning, but for conceptual thinking grounded in situated, material experimentation. The Fab Lab would not become a factory for mere toys and hobbies, but rather toys and hobbies – and tools – for creating and sharing knowledge and, it was hoped, collaborative inventiveness. If the vision included prospects for a more sustaina-

11 Most notable were the numerous workshops organized by professors and researchers in the media department connected to their topics of interest: museums and exploring the notion of open culture, new ways to educate children and young people, and identifying and materializing the benefits of Open Design and open innovation in traditionally structured businesses.

12 www.sourcemap.com (accessed 23 April 2015).

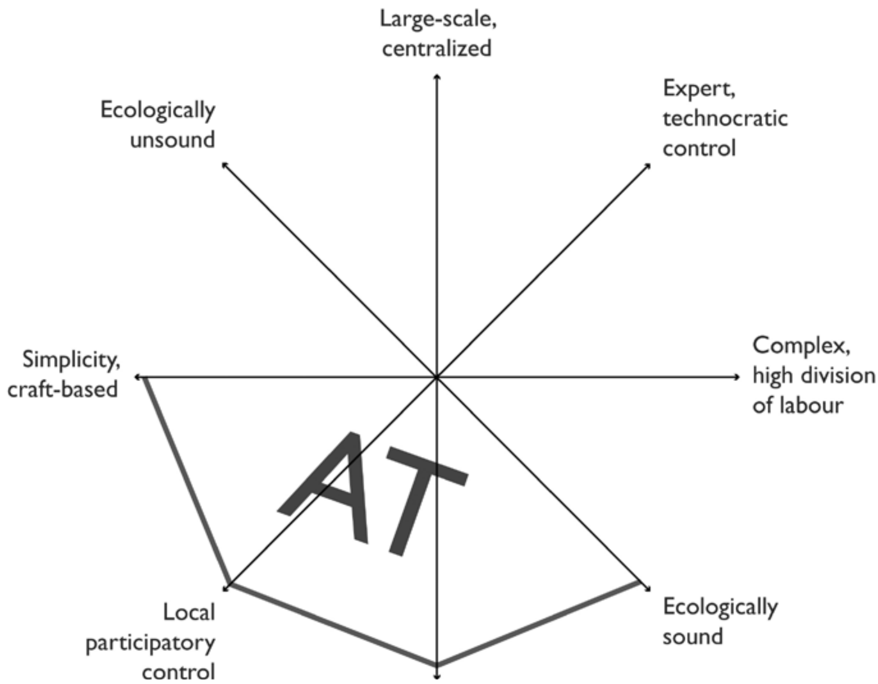


FIGURE 4: The Alternative Technology frame for technology development (source: Smith, 2005: 111). Reprinted with permission.

ble society, the prospects remained fragmented, only partially verbalized or recognized and dependent on circumstances and particular actors.

FAB LABS AS COUNTERCONTEXTS

Fab Labs are clearly alternative spaces, ideal contexts in which to observe how social groups carry out activities and how people adapt their lines of action to each other. Making (encompassing personal fabrication, hacking, DIY and other related terms) is to be seen as a challenge by these actors, makers, to the dominant mass production system: it becomes a scene in a 'technological drama' (Pfaffenberger, 1992). These groups take digital manufacturing technologies and facilities and decentralize and distribute them. They defuse the power or status attached to them and put them in their own hands: infuse them with their own meanings. Gershenfeld wrote: 'As the tools for personal fabrication now make accessible not just the use but also the creation of technology, users rather than pundits can decide which problems need solving' (Gershenfeld, 2005: 251).

This is an active reshaping of the technologies that goes beyond mere access or some amount of control; technologies themselves are appropriated and modified, the most salient example in Fab Labs being the RepRap open source 3D printer and its successors. Counterartefacts like these need countercontexts: hence the rise of makerspaces, hackerspaces and Fab Labs. Makers create an ideology to support their actions, in what Pfaffenberger (1992) calls 'antisignification'. They stage events such as FABx and open hardware festivals as performances and rituals. Altogether these processes form a stage in the technological drama that Pfaffenberger (1992) calls 'technological reconstitution'.

To understand Fab Labs therefore, one must understand the aspects of the hegemonic status quo being appropriated and reconstituted. Smith (2005), for example, illustrated the Alternative Technology movement's strategies and discourse of the 1970s as a set of socially constructed oppositions to a dominant but undesired regime (Figure 4).

Within the Fab Lab network, some actors inveigh against maker orientations seen as commercial, proprietary and conforming to the existing industrial structure; others align themselves with the side of the maker movement associated with its namesake: Make magazine and Maker Faires as produced by the Maker Media corporation.[13] Ideology therefore clearly does not dictate action, and what results are statements such as the following: 'We contend that 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 in and disseminate these practices complicates, but does not negate, their revolutionary nature' (Tanenbaum et al., 2013: 2609).

The inconsistencies in how Fab Labs are currently justifying their actions are increasingly provoking reactions of their own, as this essentially embodies how citizens seem to be engaging with emerging technologies. Nascimento (2014) proposed that current narratives on making 'are popularizing a certain meaning of technology that may grow afar from more critical and democratic understandings'. Another critic wrote that, 'digital fabrication technologies seem to be increasingly turning into mere tools for new sorts of commercial entrepreneurship that can instead give new breath to the industrial age' (Fonseca, 2015: 4). Such reactions should be seen as a natural part of the antisignification processes involved: a series of counterstatements intended to highlight weaknesses in what the original counterstatements, countercontexts and counterartefacts appear to represent.

As a tactic to achieve a more critical sociotechnical understanding among more citizens, 'Critical Making' is framed as a 'mode of materially productive engagement', enacted as a set of participatory activities that is both physical and conceptual (Ratto, 2011; Ratto and Boler, 2014). Critical Making as rhetoric also challenges makers to hold a mirror to their own activities, to address the perceived 'lack of critical discourse outside of the corporate imagination' (Hertz, 2012b). The agenda is to criticize 'the path apparently taken by maker culture that is addicted to novelty, becoming consequently toxic, unsustainable, superficial and alienating' (Fonseca, 2015: 20). The objective is also to ameliorate this culture from within.

MAKING VISIBLE THE GAP BETWEEN IDEOLOGY AND PRACTICE

The Fab Lab in this study, in a relatively short time and with limited resources, accomplished unequivocal success in bringing the principle of open community access to an otherwise closed university. The Lab has indeed become

13 http://makermedia.com (accessed 23 April 2015).

a place of diversity and mutual influence, where students of different disciplines mix and converse and peer-learn with each other as well as outsiders. Tactics to encourage even more experimentation as well as collaboration, and on topics regarded not only as exploratory and educational but also environmentally responsible, are beginning to find a foothold.

Nevertheless, as seen in this Lab, localized, distributed production may be espoused, but Fab Labs seem generally unwilling or unable to prioritize local sources of tangible materials or local destinations for waste. The actors in this Lab came to acknowledge the importance of local sources also for *intangible* ideas to justify the making: locally relevant by virtue of being connected to personal expressiveness and/or community needs. Such a vision needed to be not only actively revisited and visibly enacted, but explicitly communicated to external stakeholders.

Actors also tend to stand for certain principles and resources. They make the invisible visible, whether through a simple action of having other Fab Labs on a screen (representing the Fab Lab network), conveying Fab Lab culture (Digital Craft) by making pencil holders on the laser cutter, or listing tasks' levels of priority in a shared software tool. Invisible environmental issues and the invisibility of other aspects of ideology, i.e. not represented in practice or made salient by other means, may debilitate precisely because they are not seen and noted. As Fab Labs mushroom and their user base grows, these problems may 'cascade', (Star and Strauss, 1999: 20). In the Fab Lab in question, the supply chains remained invisible even while the waste began to accumulate (Figure 3). In essence, the waste was invisible in plain sight. Only once it was conveniently stacked beside the laser cutter, where users saw what material was available, did the waste problem slowly begin to decline. Similar if not more formidable challenges relate to seeking to improve the energy consumption and energy source issue in Fab Labs, calling equally for sustainable design strategies as the visualization in this example.

Some Fab Labs do have broader agendas, and they can influence other Labs by example. In one Fab Lab in the Asia-Pacific region, supply chains are rendered visible by restricting materials to only those that are locally supplied *and* environmentally benign. In the Valldaura Self-Sufficient Lab, the oft-used phrase 'pathways for production' offers a concrete vision on the New Industrial Revolution or new post-industrial paradigm aspired to, especially when combined with descriptions of metabolism, life cycles and new material experiments. Valldaura is a much-admired Lab and a seminal example lauded in published accounts by the network and Fab Foundation (e.g. Lassiter, 2013), yet other Fab Labs find it challenging to create such a distinct vision, not to mention act on it. Nevertheless, as a 'space of compromise', what is being sacrificed seems to be little discussed.

Figure 5 illustrates the flows of both materials and ideas in and out of a Fab Lab and how in this Lab, Digital Craft was the guiding construct for how to make responsibly and Open Design the guide for why to make. In a Fab Lab conscious of the sustainability implications inherent in its ideology, *place* is local, situated and contextualized: it is the source of tangible inputs such as local materials as well as the destination for waste that, if not preventable, is designed to be circular. The local *community* is the source of immaterial or transmaterial inputs such as local needs, which imbue the fabricated artefacts with meaning and justify their existence.

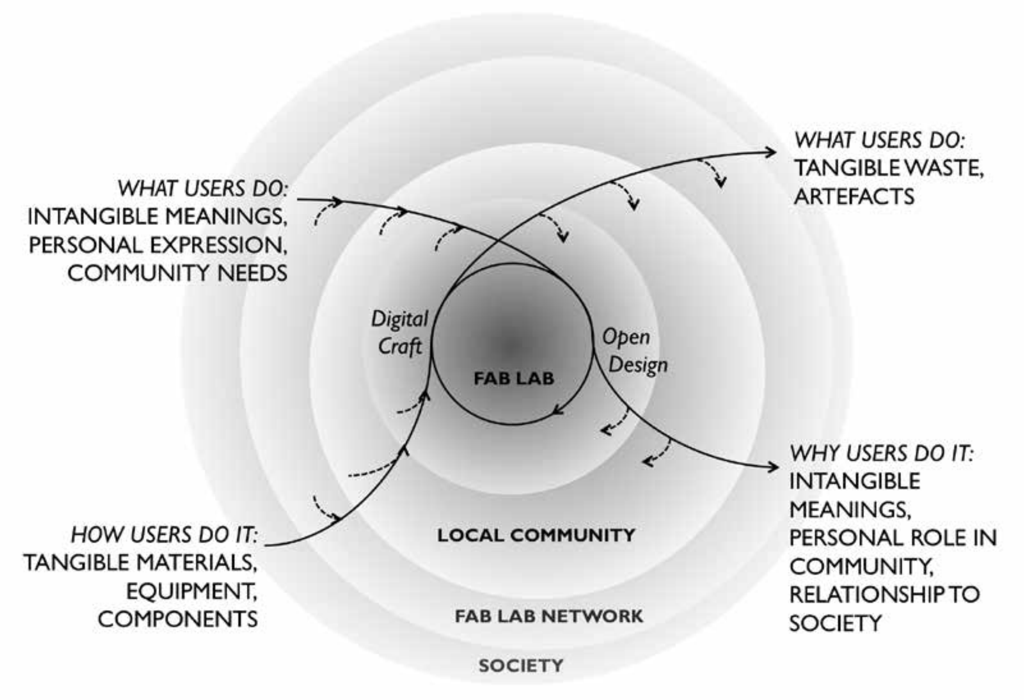


FIGURE 5: The metabolism of a sustainability-oriented Fab Lab conscious of its own cycles of materials and meanings. The ambition of a 'critical making' programme is also to detect the weaknesses in the cycles, the invisibility of energy and material flows or the lack of attention to meaning.

CONCLUSIONS

This article has examined the ideology of the Fab Lab world and how sustainability may be embedded in it by focusing on the making of one Fab Lab in a design school. The study has articulated how Fab Lab ideology, referring especially to the principle of opening access to technologies and the means of production, is enacted in practice, with some espoused values disappearing in the wake of the immediate, the salient, the visible, the convenient and the practical – i.e. the mundane and routine. In parallel, issues related to environmental and social sustainability tend to travel erratically through this discourse and even more erratically in practice, becoming alternatively strengthened or weakened due to the daily life processes in the Lab and the peculiarities of personal fabrication practices.

This discussion has been set in the context of a broader understanding of reconstitutive practices, which aim to shape technologies and discourses to a social group's own purposes. The study has illustrated how Fab Labs are counter-contexts defining their own ideologies in opposition to a hegemonic status quo, but in so doing display diverging action strategies. Time constraints and everyday routines compete with the need to articulate and operationalize vision; other actors and social worlds arise to voice their opposition to the deflation of meaning or societal responsibility.

The main findings and their implications can be summarized as the following:

1. People in Fab Labs are so busy 'putting out fires' that they simply do not have the time to enact ideology, even when they espouse it. Principles for social action must be embedded in routines from the outset, like a healthy diet, or they need systematic prompting.

2. These busy agendas as well as ideologies that do not dictate courses of action mean that Fab Labs are currently largely unaware of what they are promoting and their activities are seen by many as meaningless.

3. While Fab Labs may 'inherently' be counterspaces for distributed production and distributed design, they may not be counterspaces promoting environmental sustainability as core to their ideology. If it is desired that environmental issues are closer to the core, they need to be moved further up the agenda, via strategies for visibility and conscious practice.[14]

In Fab Labs, sustainability understanding may be best built upon an approach such as critical making: a conscious dialogue between what is done from scratch, what is to hand, and what is done from spec, with design. As a space of compromise, a Fab Lab is where users come to understand the possibilities of the digital realm by constraining it to existing resources and skills. Fab Labs also provide an appropriate platform for experimenting with the type of societal structures actors deem desirable and the future they wish to build – given this future vision is made explicit. In northern Europe, the largest user base of Fab Labs comprises design and architecture students. Fab Labs are therefore one of the interfaces through which designers come to understand their future profession. For those who choose the path of Open Design and/or distributed production over conventional mass production, as the Lab in this study has shown, Fab Labs offer a relatively risk-free platform for such exploration. However, commercial services in digital fabrication are rapidly expanding and Fab Labs may easily become subsumed in the normal business of digital production and 'tech shops'. If they are associated with other institutions such as universities or municipal actors, they will encounter ever more pressure to account for their funding and communicate their impacts. Socio-environmental sustainability is likely to count among the most important concerns, given the maker movement's position in the production of tangible artefacts using rapidly changing processes and materials.

The findings and conclusions in this study are generalizable to any community involved in making, as the problems with time management and the difficulty to identify, forge and sustain the connection with the most important stakeholder communities are fairly universal challenges. They also apply to any counterspace for practicing Open Design, a space in which the future of a new post-industrial revolution is being rehearsed already now. There are clear windows of opportunity for more environmentally sustainable practices in such a revolution, but they need to be consciously adopted.

14 To be fair, there are several inter-Lab projects (global projects on which several Fab Labs collaborate physically and virtually) that are clearly non-commercial, socially beneficial projects, some of which do take environmental sustainability into account. One may conclude that the sheer visibility of these projects better ensures the principles and drivers by which they are designed and realized are seen as 'sustainable'.

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Citizens are increasingly involved in the design and production of their own products. Forerunner groups are exploring new ways of doing things with digital fabrication tools, a phenomenon known as the maker movement. Especially communities who work together in dedicated spaces, makerspaces, are rapidly proliferating. They are of research interest, as they are now experimenting with new practices and organizations that indicate the possible impacts of a digitalizing society. They carry potential to do away with the negative environmental impacts associated with mass production and consumption (and decouple them from socio-economic prosperity), but there may also be new, unforeseen environmental consequences of such prosumption.

This dissertation reviews the environmental issues in the maker movement, and it examines how environmental sustainability is taken up in Fab Labs (fabrication laboratories) or remains invisible and unaddressed, based on longitudinal analysis. The thesis sheds light on our possible futures, as these niche activities move towards the mainstream. It clearly demonstrates how communities attempt to enact ideology: how we shape technologies and technologies shape us.

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