Christoph Schneider

Opening Digital Fabrication: Transforming TechKnowledgies

KIT Scientific Publishing

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by
Christoph Schneider

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Abstract

During the past decade individuals and organisations have started to collaborate in the development, production and usage of digital fabrication machines such as 3D-printers, laser cutters or milling machines and to 'open source' knowledge about these. A global field of 'open digital fabrication' has emerged in which knowledge and technology are produced and organised to foster the public access to and the shared usage of these digital machines. Technosocial arrangements have been created and explored that transgress industry and institutionalised technoscience and combine these new technologies with visions of future technical capabilities and normative desires for 'openness' and inclusion. The emergence of open digital fabrication, however, is inextricably entangled with the dynamics of digitisation and technoscientification. Through digitisation relations between people and objects are increasingly seen as digitisable, and technoscientification has spread claims and aspirations of a technological design of society that is increasingly taken up and transformed in many areas. This book develops the concept TechKnowledgy to analyse open digital fabrication as a field of digitisation and technoscientification, which produces and organises technology and knowledge in particular ways. Through this historically emergent and dynamic collective procedures come into view that entangle the becoming of technical objects, subjects, organisational forms and desires, i.e. they produce and organise particular forms of technology and knowledge. The concept enables a shift from 'technology' seen as technical objects towards the collective technological processes in which these are imagined, developed, produced, used and transformed, which are also processes of the formation and transformation of technosocial worlds.

Based on different qualitative methodologies, such as interviews, participant observation and notably action research, the TechKnowledgy of open digital fabrication is analysed in two cases. The first study reconstructs the production and organisation of knowledge in an open source laser cutter development project based upon voluntary online collaboration. It is shown how particular technical objects are fundamental to the qualities of the produced knowledge. The project is mediated by the object of the laser cutter. This object and the project are organised together in a process that makes technological knowledge public. The chapter shows that the TechKnowledgy of open digital fabrication depends upon specific constellations of various technical objects. The second study is concerned with the spread of FabLabs, a loose global network of by now more than 1,000 organisations that aim to make digital fabrication locally accessible. The emergence of the concept at the Massachusetts Institute of Technology is analysed and how this at the same time entangled with and transgressed institutionalised technoscience. The study then turns towards the foundation of a non-profit FabLab in Germany in which I was involved as action researcher. It is analysed how the FabLab concept is mobilised and produced in a particular version by a group of citizens. The chapter interprets the history of FabLabs as well as the foundation of the mentioned FabLab as a collective real-life experiment in which different actors explore forms of organisation to foster the local and 'open' access to digital fabrication processes, observe each other and unfold the TechKnowledgy of open digital fabrication in the process.

The book concludes by identifying the central procedures that define the TechKnowledgy of open digital fabrication. In light of digitisation and technoscientification, however, open digital fabrication is only one novel TechKnowledgy and other transformations of TechKnowledgies are becoming visible. In the contestations for the different ways of how technical becoming is entangled with the becoming of (possible) technosocial worlds engaged forms of sociology and science and technology studies could play an important role in transforming TechKnowledgies.

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Karlsruhe, June 2018 Christoph Schneider

1 Introduction

The future of digital fabrication is opening. Computer numerically controlled (CNC) machines and the design and production of material objects through them has again become a public matter. The last time that these technical processes spurred years of public debate was when after the Second World War computer numerically controlled machinery was being developed and implemented in factories to automate aspects of manual labour. This form of rationalisation through digital machines in factories was strongly opposed by some and embraced by others, but it has not stopped since then. If you had asked an observer in the 1970s or 1980s about the consequences of CNC technologies, they would probably have said: more automation, more deskilling of manual work, more efficiency in industry resulting in more output and more control of workers[1]. If you asked someone today who is familiar with 'open digital fabrication', the focus of this study, you would get another answer: more technical capabilities for diverse individuals, a re-skilling of consumers, customised and independent production of objects and global collaborations of so-called 'makers' that make factories obsolete and spur new forms of decentralized economies[2].

Besides such changes in the narratives other aspects are different in the new sphere of open digital fabrication. While in factories workers are paid to operate the machines to produce commodities that are defined by the company, diverse groups of people, sometimes referred to as makers, have started to pay money to access CNC machines to produce things that they want. And they have even started to organise these machines in special ways. Many people – professionals, amateurs, hobbyists and volunteers – have invested years in developing and improving CNC machines in projects that are often based on online collaboration and open-source approaches. Many of the resulting designs for the machines and for objects that can be produced using them circulate on the Internet and can often be publicly accessed and downloaded for free. Whole publics have emerged that do not simply discuss and debate but produce and use these technologies. Novel organisations such as FabLabs[3], 'fabrication laboratories', have been founded to make digital fabrication locally accessible to individuals and groups and, for example, courses are being given to schoolchildren to explore and understand this new world of open digital fabrication.

It seems that open digital fabrication has barely anything in common with the older and still dominant forms of digital fabrication in industry. One even only touches the tip of the iceberg by saying that cheaper and smaller versions of CNC machines have become available. Also the technical definition of digital fabrication as 'an evolving suite of capabilities to turn data into things and things into data' (Gershenfeld, 2012, p. 57) does not dig much deeper into the opened future of digital fabrication. Rather, during the past one and a half decades novel processes and procedures that turn data into things and things into data have come into being that enable such conversions beyond established institutions. People who have never seen a factory shop floor are in contact with digital fabrication, and no longer are companies the sole or even prime agents in using small-scale and flexible forms of CNC machinery. This study is about the specific forms of intervention, production and circulation of technology and knowledge in open digital fabrication. In a more general sense, it is about the relationships of technology and knowledge and their relation to human becoming – relationships that have begun to fundamentally change and to open different possibilities for the unfolding of technosocial realities in contemporary society.

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[1] The classic social history of this wave of industrial automation is David Noble's (1984) *The forces of production*.

[2] Such 'revolutionary' narratives have been brought forward by Anderson (2012) and Rifkin (2014), for example.

[3] I use the spelling 'FabLab' since it is used in FabLab Karlsruhe, which I have co-founded. Other spellings such as Fab Lab, fab lab or fablab also exist.

Open digital fabrication has manifested itself in many material instantiations. Some are peculiar in their appearance, such as the following example, especially when compared to high-gloss commodities.

The image on this book's cover shows a sculpture by an artist that I became friends with and whose work I came to appreciate through my research on open digital fabrication. It is a sculpture that was 3D-printed in a particular way. The sources that the artist used for this sculpture are digital data sets from his own smartphone – call detail records and movement data. To create such sculptures these data are transformed into three-dimensional digital drawings that serve to instruct the printer. He reshapes, stretches or remixes the drawings using computer-aided design (CAD) software. For the printing he goes to a close-by FabLab, which in this case is a member-based non-profit organisation in which he is actively involved. The FabLab operates a workshop for its members to access and to use 3D printers and other machines of digital fabrication, such as a laser cutter or a CNC milling machine. The printer he uses was bought from a company that builds these machines based on publicly accessible open-source designs and contributes to this public knowledge. If properly instructed and operated, the machine heats up a particular kind of plastic, which has become the iconic material for such forms of relatively low-cost 3D printing. Through moving a heated nozzle in three dimensions within a defined area the printer builds up three-dimensional objects layer by layer of very thin and hot filament which then cool down and become solid. This is also the reason why technically the term 'additive manufacturing' is more correct for this process. However, the artist does not only have the printer fabricate the object that he digitally designed, but he also manually interferes with the printing process. By changing the unfinished object's position or by changing the printer's adjustment, the artist makes sure that the material production process changes the form of the object as well, such that the printed object only slightly resembles its digital template. By the time the object is taken out of the printer, only fragments of it resemble the data set at the beginning of the process.

This object, which is based on a process with different transformational phases, is a curious document of how an artist interferes in two interrelated processes: the unfolding of digitisation and the emerging technology of 3D printing. On the one hand, the idea of simple and perfect transmission of digital data, hailed by its supporters and feared by its critics, is challenged through digital and material transformations that leave but a fraction of the initial information recognisable. On the other hand, the idea of a perfect controllability of matter and of a continuity of digital and material objects, which is often ascribed to 3D printers, is exposed through the manual and bodily engagement with the machine that is central to achieving the final sculpture. This object in short is a perplexing document of fundamental and ongoing changes in particular relations to technical objects. Besides challenging interpretive frames and cultural tropes concerning technology the object was born out of a particular way of interfering in contemporary technology.

In asking how this artistic object was made possible, it is not enough to ask the artist about his ideas or artistic skills. Rather, there is a whole 'collective machine'[4] (cf. Deleuze and Guattari, 2004) that enables the artistic process. This is made up of technical objects, particularly digital objects, such as CAD software or data sets. But also the printer, itself a curious combination of software, electronics and mechanical technology. Then there are subjects, such as the artist, who position themselves in relation to these objects and act with and transform them, such as the thousands who helped produce many of the open-source components and the design of the printer by collaborating 'online' and by publicising the knowledge produced. Therefore, there are also the combinations of organisational forms, some of them 'online' and others in material places, such as the FabLab, where the machines are provided as a common resource. There are also particular desires at play of participating in the transformation of the objects and the dynamic process of which they are a part. Desires that are also expressed in and produced through visions and imaginations

[4] More often this is referred to as 'assemblage'. For reasons argued for in chapter two, I use the notions 'collective machine' or 'machinic assemblage' to refer to the complexes that are central to the thought of the two philosophers.

of why these digital technologies are so important as to artistically interfere in and with them. This collective machine enabled the artist to produce his art object in a process in which he drew upon and transformed knowledge and technology, which eventually also transformed him.

1.1 Open digital fabrication within society

Such interferences with digital fabrication technologies and the resulting transformations are not confined to avant-gardist or subcultural niches in which only artists might experiment. Open digital fabrication has become a highly dynamic field attractive to, observed and practised by many different people and organisations. This attractiveness of open digital fabrication is based on its various associations with other recent phenomena that have been changing the landscapes of technology and knowledge. Open digital fabrication, since its emergence about one and a half decades ago, has been dynamically unfolding within a digitising society that increasingly looks towards novel technical capabilities to transform itself, as it gives technoscience a central place.

A growing body of studies from different disciplines has been emerging during the past years that either explicitly addresses open digital fabrication or closely related phenomena such as the ‘maker movement’. For example, it has been investigated from the perspectives of ‘openness’ and design (van Abel et al., 2011), 3D printing and intellectual property (Söderberg and Daoud, 2012), the motivations of open-source 3D printing developers (Söderberg, 2013a), making and community (Gauntlett, 2013), makers and gender-based exclusions (Toupin, 2014), customisation and the body (coons, 2016), making as post-capitalist practice (Baier et al., 2016), making and citizenship (Davies, 2016), FabLabs and sustainability (Kohtala, 2016) or the visions and utopias of 3D printing (Dickel and Schrape, 2016). Often, these studies take their inspirations or motivations from the partly grand expectations that entwined with the emergence of open digital fabrication. These, however, are not only based on open digital fabrication but on many related dynamics within which it has unfolded. Following the insights of existing research, I situate open digital fabrication within the growing attention towards ‘open knowledge’, the emergence of the maker movement, the reconfiguration of political economies, and the related processes of digitisation and technoscientification. When considered within these processes, open digital fabrication finds itself in a landscape with a profound sense of change.

Open digital fabrication, like many other spheres of knowledge production under the banner ‘openness’, has been strongly influenced by open-source software. Nowadays, many people know open-source software projects such as Linux or collaboration projects such as Wikipedia, which draws upon organisational forms and normative frameworks that were initially brought together in free software development in the 1980s. Later on, the term open-source software became dominant[5]. However, with the spread of the Internet these ideas and practices of making digitised knowledge public, available and modifiable became increasingly attractive to other spheres of knowledge production with which open-source practices have entwined and transformed (Kelty, 2008). Nowadays, there are many diverse projects and aspirations of ‘openness’: ‘open data’, ‘open government’, ‘open art’, ‘open-source ecology’, ‘open education’, ‘open-access science’ and many others. And there is ‘open digital fabrication’. Within open digital fabrication there are many projects that descended from software development as they develop technical objects for digital fabrication in an

[5] Although the history of open source began with ‘free software’, in the late 1990s the notion ‘open-source software’ became dominant, also because it was more compatible with corporate cultures (Stallmann, 2010; Kelty, 2008). Open source points at the dual technical structure of software. Underneath the surface that you encounter as a user is the machine code which instructs the computer hardware and is not human-readable. However, translations between such machine code and human-readable computer instructions exist and are used to programme software. This the source code. In a way, this is the design blueprint of the software. Open-source hardware or open hardware is the main way the ‘open-source hardware movement’ labels itself in analogy to open-source software.

open-source approach. The notion ‘open-source hardware’ emerged to denote such and similar projects that combine open-source practices and material technologies. In particular the ‘RepRap’ project, launched in 2004, has led to many open-source designs of 3D printers, gained much prominence and arguably was highly influential in creating non-industrial 3D printing oriented towards individual users. The recent hype of 3D printing (cf. Alvial Palavicino, 2016) was also strongly spurred by these machines that were neither developed nor produced in industrial settings and, therefore, suggested that material technologies and their organisation are on their way to increasingly adapt to the distributed logics of the Internet and digitisation.

Openness, however, can no longer be reduced to a coherent set of causes or effects, if that was ever possible. The discourse of practitioners and academics alike has for a long time tended to idealise open-source projects as a form of collaborative economy based upon self-organised communities of volunteers that share knowledge. The picture is more diverse, however. By now, open source has become a standard approach in the software industry and almost every major IT company is involved in open-source projects often closely related to their product and innovation strategies (Schrape, 2016; Kelty, 2013). In other areas, such as open digital fabrication, however, openness is not as established and still a more inventive and experimental approach. Whether or not open digital fabrication will have the same fate as open-source software cannot be predicted, but its practitioners span from grassroots activists to multinational corporations. Openness, furthermore, is more than an approach in projects that develop technical objects and publish the designs online. Rather, with its connotations of transparency, collaboration, participation and publicness, openness has become a widely used and differently desired political term that signifies new networked and digitised modes of coordination and organisation (Tkacz, 2015). Openness is contested, diverse and highly relevant, as it is being deployed and practised by small communities of volunteers up to governmental ‘open innovation’ strategies. Within these dynamics open digital fabrication has occupied a central place for experiments with the ‘opening’ of material technologies.

Related to its openness, the figure of the ‘maker’ emerged in connection with open digital fabrication. While there has been a renewed surge of attention for do-it-yourself (DIY) practices championed by various groups, magazines, events and platforms that come together under the umbrella term ‘maker movement’, the iconic technology in this movement has been open-source 3D printing. Empowered through such capable machines, makers are often seen as the avant-garde that is producing and using technology in highly individualised, yet collaborative ways. However, besides 3D printouts many different things are made in ‘making’, such as clothing, furniture, electronics and window gardens. Through sharing knowledge and tinkering some claim that makers do away with divisions of labour between producers and consumers (Gauntlett, 2013; Anderson, 2012). Makers, however, can now be found in many places, in counter-cultural makerspaces, in universities, in companies, at ‘maker faires’ and even addressed in governmental calls for research and development projects, as happened in Germany in 2016[6]. The rise of the figure of the maker has, therefore, also been the spread, diversification and novel legitimation for DIY, tinkering, hacking and the creative appropriation of technical objects through a diverse group of people.

An important part of the growth of the maker, however, have been novel organisations that explicitly aim to provide the infrastructures for making. In particular FabLabs, notably launched at the Massachusetts Institute of Technology (MIT), have become central organisations to foster open digital fabrication. By now, around 700 such labs exist around the globe based upon the idea of providing access to digital fabrication machines for individuals and, therefore, complementing the digitally networked aspects of openness in open digital fabrication. Besides this common aim, FabLabs exist in different forms, with or without formal ties to MIT, and can be found from small, volunteer-run labs with low budgets to labs hosted by a university or company with equipment worth hundreds of thousands of euros. This diversity of the labs in

[6] See for example the competition ‘light cares’ by the Federal Ministry of Education and Research (https://www.bmbf.de/de/light-cares-wettbewerb-zehn-projekte-ausgezeichnet-3269.html, accessed October 2016).

a way reflects the mentioned diversity of making. However, FabLabs have been places for enthusiasts and others alike to learn about and to experiment with digital fabrication and other technologies in settings where professionals and amateurs can be found. Besides FabLabs there has also been a rise of similar organisations such as makerspaces and hackerspaces, which also reach out to particular audiences as places for tinkering and experimentation with the entanglement of digital and material dimensions of technologies. Not least through the above-mentioned developments some authors have started to claim that makers are the bearers of a ‘new industrial revolution’ (Anderson, 2012; Gershenfeld, 2012).

Such revolutionary discourse, however, has found its resonance within wider dynamics of digitisation and changes of political economies that are under way. Whether ‘open’ or not, digital fabrication and related developments in digitisation have led many authors to speculate that fundamental changes in the way in which things are developed, produced, transported and used are on the horizon. It is said that these technologies may foster a renewal of manufacturing in rich countries where decentralised but high-tech factories produce customised things on demand. Thus, along with these new technologies much more interactive settings between customers, producers and users of digitally fabricated products are expected as well as novel business models and economic arrangements (Birtchnell and Urry, 2016; Ferdinand et al., 2016). Yet, even beyond digital fabrication, advances in digitisation and in technoscience, e.g. in robotics, have also spurred a wider discourse of a ‘next industrial revolution’ (e.g. Mason, 2015; Rifkin, 2014) or of ‘industry 4.0’ (Pfeiffer, 2016) based upon wide-ranging automation and digital coordination and control. Although these discourses vary in their focus and judgement of these possible transformations, they share in common the belief in the fundamental impacts of digitisation on material economies and in the power of technology to bring about these changes. Such discourses, however, are taking place in light of tremendous dynamics of digitisation that have fundamental impacts in all spheres of society. Information technologies and their connections multiply, and digital information is forming all kinds of complex dynamics that change how people and organisations know, communicate, organise or work (Castells, 2002). Digitisation affects people and objects and the relations between them, senses of self and other change and increasingly the world is seen as a field of possible or impossible and contested digitised and digitisable relations (Hörl, 2013a; Thrift, 2011).

The ‘revolutionary’ appeal of open digital fabrication also resonates with a society that construes and constructs its futures increasingly in light of and informed by technoscience (Nordmann, 2016; Urry, 2016; Jasanoff, 2015; Grunwald, 2014). In such an unfolding ‘age of technoscience’ (Nordmann, 2011; Forman, 2007) the symbolic and material products of technosciences such as computer science, nanotechnology or biotechnology increasingly set the terms by which technologised societies govern themselves. As the philosopher Nordmann (2011, 2012) has argued, the rationality of technoscience seeks to find, unfold and control novel technical capabilities and, therefore, differs fundamentally from the rationality of classical science that seeks better theoretical explanations for understanding the world. Technoscience engages in an ontological project of technically redesigning the world. It promises to solve all kinds of societal issues with these novel technical capabilities that are often not yet materially existing but are envisioned. The age of technoscience presents itself to many of its observers full of messy arrangements, fears and hopes, novel technologies and forms of life. Key to the success of technoscience is that its products and rationalities are not confined to universities and laboratories. Rather, as classical diagnoses already put it, technoscience transgresses and combines different societal spheres through which various mixtures of technologies, socialities, natures, politics and selves unfold (Haraway, 1997; Latour, 1993). As a consequence, exploring and unfolding technical capabilities has become a widely diffused and shared imperative in societies that set out to ‘co-design’ their technoscience (Nordmann, 2016; Latour, 2008). Furthermore, digitisation and technoscience enforce each other in that both bring forward an ontology centred on information and the belief in the malleability of matter, life and society through the manipulation of information (Harari, 2016; Milburn, 2010). The project of technological world-making of technoscience has, therefore, diffused into an unfolding process of ‘technoscientification’ of society.

1.2 How to study open digital fabrication?

Open digital fabrication with its 'open' forms of organisation, enthusiast 'maker' subjects, digitised and unfolding technical objects and its desires to digitally re-fabricate the world has been entangling with the above-mentioned dynamics. Not only has it been influenced through these, but it has been and continues to be an important field for concrete manifestations and experiments within such an unfolding world. Furthermore, open digital fabrication has been a highly dynamic phenomenon that is inherently changing. However, we still lack a clear understanding of open digital fabrication as a field of practice that is entwined with these societal transformations.

The question of this study is, thus, how has open digital fabrication been becoming? How has open digital fabrication been unfolding as a field of digitisation and technoscientification that produces and organises technology and knowledge in particular ways? How, that is when, where, by what and by whom, is knowledge and technology produced and organised as open digital fabrication? What are the particular qualities of knowledge and technology that make up open digital fabrication? What are the processes, trajectories and affordances for action and intervention in technology and knowledge that open digital fabrication offers and that have been creating it in the first place?

Open digital fabrication then comes into view as a specific form of the intertwined becoming of people, technical objects and knowledge. This shift towards processes of becoming is necessary to grasp open digital fabrication as an unfolding phenomenon in contemporary society that is pluralising the conditions for the becoming of technology and knowledge. Open digital fabrication is a central field where such novel conditions of the production and organisation of knowledge and technology have come into being. Understanding how this takes place is, therefore, also central to understanding trajectories of the unfolding of contemporary digitising and technoscientificating societies. The conditions and forms of acting techno-*logically* are changing enormously, and the powers to do so are diffusing and are being rearranged. Open digital fabrication is a pre-eminent case in these dynamics, as it produces and organises technology and knowledge in non-industrial ways. This study develops an analytical framework and pursues empirical investigations that make the above-mentioned transformations analytically compatible to investigate the new technosocial realities that have been coming into being.

Indeed, studying how knowledge and technology entwine is one of the key foci of science and technology studies (STS). One might even say that the field defined itself due to its insistence that there is no such thing as 'universal knowledge' or 'neutral technology' but only the simultaneous production of both within particular contexts. The 'laboratory studies' showed how scientific knowledge is produced within practical engagements of scientists with their laboratory equipment. The 'social construction of technology' showed how technologies are always shaped by social processes of meaning-making. And studies into 'sociotechnical systems' and 'actor-networks' showed how technical artefacts are always part of heterogeneous social arrangements[7]. Of course, I draw inspiration from such classic perspectives when I ask about the relations of knowledge and technology in open digital fabrication. This phenomenon, however, presents a further challenge to its analyst: it is not only that technical artefacts are shaped by particular people in particular contexts in open digital fabrication. To understand open digital fabrication the analyst has to understand how the conditions for such knowledge productions have been established in the first place. The analysis needs to be able to grasp how particular actors and organisational forms are either produced or made affordable for the productions and organisations of knowledge and technology of open digital fabrication.

[7] For revealing retrospective evaluations of these conceptual innovations in the 1980s by leading figures of the field see Bijker and Pinch (2012), Knorr-Cetina (2007) and Latour (2005).

Such a fundamental perspective is required in contemporary times when phenomena like open digital fabrication emerge in the interstices of established industrial or scientific institutions and their deeply normalised ways in which the becoming of people, technical objects and knowledge are arranged[8].

Open digital fabrication is, furthermore, a phenomenon situated in history. It has been located within historical contexts and it is practised as a highly dynamic set of processes that aim to unfold digitisation and technoscientification in particular ways. An inquiry into open digital fabrication should, therefore, also be able to trace and analyse the ways in which its productions and organisations of technology and knowledge have been entwined with and adapting to a changing environment over time, not least since open digital fabrication is still unfolding and changing. Part of its history has also been its close connection with the spread and diversification of the Internet during the past decades. From early on, open digital fabrication has been a highly networked and globally spread phenomenon with much of its processes taking place 'online' and with images, files, data, videos and other forms of explicit knowledge circulating online and contributing to the decentred and diffuse coordinations of the phenomenon. Consequently, an inquiry into open digital fabrication should also be able to analyse the conditions for the relatively fast diffusion of open digital fabrication[9].

The desiderata for an analysis of open digital fabrication require certain conceptual and analytical innovations for which different strands of research have laid the ground. As open digital fabrication has been transgressing established institutions and conceptions of technology and knowledge, it is necessary to transgress particular traditions in STS and sociology. In this study I approach open digital fabrication along the following lines, not afraid of encounters with different disciplines or of the need to entwine theory and detailed empirical study in the mode of bricolage. The mode of inquiry that I pursue in this study brings into contact different theoretical and practical approaches to the study of the becoming of technology and knowledge. For complex insights into a complex phenomenon like open digital fabrication a bricolage of different perspectives brings its various dimensions into view. My strategy is to draw upon different forms of analysis and the presentation in writing to highlight different aspects of the phenomenon. This involves a strong dialogue between theory and empirical analysis. While some strict versions of empiricism that have become popular in STS, e.g. in many ANT studies, often reject theoretical explanations, I see the various theories that I use for the inquiry as important epistemic devices. Through this I pursue an analysis of patterns of conditions and possibilities of the unfolding of open digital fabrication.

As a result of the interplay of empirical and theoretical inquiries I develop the concept of '*TechKnowledgy*' in this study. This is based upon the philosophy of technology of Gilbert Simondon (2009, 2010, 2012, 2016), relational theories of knowledge (Ingold, 2013; Collins, 2010) and the machinic thought of Gilles Deleuze and Félix Guattari (Deleuze and Guattari, 1994, 2004). The concept enables the embedding of situated manifestations of the production and organisation of knowledge and technology into wider processes and historical conditions. *A TechKnowledgy is a historically emergent and dynamic set of collective procedures that produce and organise technology and knowledge. A TechKnowledgy draws upon and transforms knowledge of technologies by using and transforming technologies of knowledge. TechKnowledgy is a process concept that inevitably is about the becoming of technical objects and of people, both of which are linked through knowledge.* It is, therefore, not restricted to open digital fabrication. Instead, there are many different TechKnowledgies in the contemporary world and phenomena such as

[8] David Noble (1977) wrote the classic study of how the conditions for industrial engineering were created and how the industrial regime of the production and organisation of knowledge and technology was born in the second half of the 19th century in a technological process of arranging people, organisations and technical artefacts.

[9] Troxler (2014) shows how the number of FabLabs grew exponentially in the first twelve years of the existence of the concept until 2014.

open digital fabrication help us see the diversity and contingency of arrangements that produce and organise technology and knowledge.

The inquiry into the TechKnowledgy of open digital fabrication is an inquiry into what it means to act and to become in the particular techno-*logical* manner of open digital fabrication. The shifts in perspective that go along with this theoretical concept are twofold. On the one hand, this is a shift towards the temporal and unfolding character of processes of the production and organisation of technology and knowledge. And on the other hand, this is a shift beyond the diagnosis that heterogeneous elements are related in sociotechnical processes – the defining ontological statement of much STS – towards an understanding of *how* particular heterogeneous elements work together to constitute specific becomings of knowledge and technology. Through this we might start to get at particular construction logics of technosocial worlds as differently assembled worlds. *The hypothesis of this study is, therefore, that in open digital fabrication a particular TechKnowledgy is visible, contested and experimented with and this gives an insight into more democratic forms of digitisation and technoscientification for which open digital fabrication is an example*. The book analyses the procedures and qualities of this TechKnowledgy in the chapters that each have a different perspective onto the entwined becoming of technological objects and human beings.

Chapter two develops the concept of TechKnowledgy through a discussion of classical and recent social theories and their focus on technology. It argues that a shift from the products of technology, i.e. technical artefacts, is necessary towards the processes and collective procedures that create and transform these objects. Such a shift is then also a shift towards the dynamic environments where such objects in becoming pass through. Knowledge in TechKnowledgies emerges through an active engagement of people with their environments, which include objects. Knowledge is produced within the dynamic relations that such an active engagement creates and it is, therefore, that which entangles the becoming of technical objects and people. The chapter also introduces another key concept of this study: collective machine. An analysis of TechKnowledgies requires an attentiveness to and conceptual vocabulary for heterogeneous relations in becoming and in process. Within the work of Deleuze and Guattari a theoretical tool to do exactly this exists with collective machine. TechKnowledgies (trans)form collective machines.

The third chapter is a case study of an open-source development project of a laser cutter. It focuses on such technical objects and asks about their role in open digital fabrication and the processes that ‘opened’ knowledge in this project. Open digital fabrication is centred around particular technical objects such as digital fabrication machines. Furthermore, these machines are connected to various other objects as open digital fabrication takes place in technologised environments not least filled with PCs, Internet connections and software. It is fundamental to take these objects into account to understand open digital fabrication’s unfolding. The ‘Lasersaur’ project started in 2010 to extend the accessibility of laser-cutting by bringing down the price of the technology by creating an open-source design and making the knowledge to build and operate a laser cutter publicly accessible. Based on qualitative interviews with key persons in the project and a participant observation of a building process of a machine the chapter analyses the role of technical objects in enabling, transforming and stabilising the project. The study reconstructs the history of the Lasersaur project and the ways in which the project produces and organises this technical object and knowledge. In fact, the project is enabled by the laser cutter. There is a recursive logic such that the object enables the project that forms the object. However, the laser cutter cannot be singled out. A whole background of diverse objects is necessary and drawn upon to build the machine and to circulate explicit knowledge about it. The production of knowledge is largely the creation and transformation of relations to these objects and the transmission of explicit knowledge based on them. The TechKnowledy of open digital fabrication in such development projects is fundamentally the configuration and connection of relatively indeterminate ‘open objects’ (Simondon, 2009) and people into a process of object-mediated communication and knowledge transmission.

The fourth chapter asks for the ways in which open digital fabrication is organised in material settings. It entails the analysis of the central empirical case of the study, the foundation and initial organisation of FabLab Karlsruhe e.V. This is a German member-based non-profit organisation that was started in 2013 and opened its doors in 2014. FabLab Karlsruhe is one of the by now many 'grassroots' FabLabs that emerged from 2010 onwards. These are often run by a community of members who typically operate FabLabs on less financial resources than FabLabs that have been hosted by a larger organisation such as a university or run as a business. The study is based on action research. As action researcher I initiated the FabLab project in Karlsruhe and helped to set it up in its first two years. The study reconstructs the emergence of FabLabs at the MIT around the turn of the millennium and the transformative process that let grassroots FabLabs emerge. Then the foundation of FabLab Karlsruhe is analysed. I argue that FabLabs constitute a collective 'real-life experiment' (cf. Krohn and Weyer, 1994), based on many different interventions with the aim to make digital fabrication accessible beyond the confines of universities or companies. A focus on real-life experiments not only enables an analysis of the entanglement of imaginations and practice, but also of the surprising and creative unfolding of open digital fabrication through its technosocial arrangements. This facilitates thinking of the present as unfolding, complex and not simply determined by the past, and as a space for possibilities and emergence, as opening to different possible futures. The conceptual shift that this study undertakes is part of a wider shift in social theory towards the processual, the temporal and the futurity of social life (Urry, 2016; Appadurai, 2013; Adam and Groves, 2007). This shift is necessary in highly dynamic times, with uncertainties about the future and multifarious interventions into the world to make and remake futures such as open digital fabrication. With a focus on the practices of creating and setting up the FabLab in Karlsruhe the chapter continues by analysing several dimensions of experimentation with the organisation of open digital fabrication. It is shown how subjectivities, collective identities and organisations do not precede open digital fabrication but their becoming is part of the TechKnowledgy as well.

The concluding chapter abstracts the key procedures of the TechKnowledgy of open digital fabrication from the empirical cases and discusses its dynamics in relation to ongoing changes of digitisation and technoscientification. Each of the chapters before, however, entail discussions of digitization and technoscientification to advance the concepts and empirical analysis. To highlight the unfolding character of open digital fabrication, the conclusion also explores the spaces of possibility set by tendencies that became visible in the case studies. Amongst these tendencies are emerging contestations between different TechKnowledgies that are unfolding beyond the settled TechKnowledgies of industry.

Due to practical constraints of individually working on a PhD and due to the 'nature' of open digital fabrication itself, its diversity cannot be grasped in a single study. Rather, my study has a particular perspective on open digital fabrication. The Lasersaur as well as FabLab Karlsruhe are projects within open digital fabrication that have been strongly driven by an ethos of voluntary involvement, empowerment for individuals and communities and a non-profit approach. One could say that both these projects were motivated by a 'democratisation' of open digital fabrication to which they wanted to contribute. Besides such projects there are many others that are organised in a more 'top-down' manner, e.g. by universities or companies. There are by now many companies, large and small, that want to have their share of the open digital fabrication market and offer digital platforms, technical objects or services for it, some even open source. I do not think that there is the one proper form of open digital fabrication or that business simply exploits the cultures and the unpaid work of volunteers and hobbyists who contribute to open-source knowledge[10]. It seems rather that they mutually support each other and are evidence for changing political economies.

[10] Tech et al. (2016) investigate the complex relationships between companies and volunteers in open-source 3D printing.

Much of the excitement for open-source practices, either by practitioners or by scholars, is based upon their peculiar economic arrangements in comparison to classical industrial or scientific ways of knowledge production. There is a huge variety of concrete economic arrangements in the open-source landscape with differently organised projects, which sometimes involve companies and wage labour and sometimes rely on volunteers or mixtures of both (Schrape, 2016; Tech et al., 2016; Kelty, 2013). Especially the recent diffusions and transformations of 'openness' make it imperative to approach open digital fabrication without theoretical idealisations[11]. Rather the concrete ways in which people, time and financial and other resources are being arranged to produce knowledge and technology and how this can entail different organisational forms need to be empirically investigated. Mainstream STS, however, has largely ignored economic processes in their studies. Only recently have some scholars argued for a political economy of technoscience (Birch, 2013; Tyfield, 2012). In both empirical studies, I show how in particular ways relations to objects, people or organisations are established that transgress such binary forms of thinking or of evaluating. Open digital fabrication is a complex and highly dynamic TechKnowledgy that works and reworks all kinds of elements, it is generative, diverse and contested. This does not mean that open digital fabrication is always the same. Instead it means one has to look precisely into concrete manifestations of open digital fabrication to understand its consequences in a particular setting.

[11] Especially early studies into free software and open-source software development have argued that these projects are beyond capitalism and are based on a 'gift economy' or purely on commons (e.g. Benkler, 2006; Ghosh, 1998). By now, although open-source projects typically create public knowledge and do not rely on strong intellectual property to make knowledge scarce, the heterogeneity of open-source projects and their compatibility with capitalism has come into view.

2 On TechKnowledgies

Open digital fabrication is filled with technical objects which have received a lot of attention, have been admired and desired and have astonished observers for the technical procedures that they can perform. During my research, I encountered many instances where, for example, a 3D printer was used to create a sense of wonder amongst visitors to the FabLab. 'See, through combining digital templates, a sophisticated mechanical design and some plastic, this machine creates tangible, three-dimensional objects for use,' was the typical statement implied in such performances. And while many other machines in digital fabrication, such as laser cutters, equally combine digital and material technology to produce objects, from a perspective on these technical objects, open digital fabrication is actually not that spectacular. Industry uses much more expensive and sophisticated versions of such machinery and, furthermore, we encounter combinations of digital and material technology almost everywhere now. Open digital fabrication starts to get interesting and unique, however, when technical objects and the ways in which they are being designed and used are considered together. Then, much of the wonder when seeing a 3D printer operate relates also to the fact that the machines have not been seen in action before, as they are literally locked away in companies that tightly regulate the access and use of the machines. In fact, if we only looked at open digital fabrication through its technical objects, we could merely state that they are small reproductions of more sophisticated objects. Yet, common wisdom and many academic theories tell us that we should focus on technical objects to understand 'technology'. This chapter argues that other concepts and perspectives on technology are needed to capture and analyse the significance of phenomena such as open digital fabrication. To do so, I introduce the concept of TechKnowledgy. Why is there a need for such a novel concept?

Technology can mean many things, and it is a pervasive notion in everyday life and in STS. 'The word technology is as capacious as it is unspecific. It covers an astonishing diversity of tools and instruments, products, processes and systems. A composite of Greek techne (skill) and logos (study of), "technology" in its earliest usage, back in the seventeenth century, meant the study of skilled craft. Only in the 1930s did the word begin to refer to objects produced through the application of techne' (Jasanoff, 2016, p. 8). One of the reasons why technology only refers to technical artefacts has probably to do with the dominance of industrialism from the early 20th century onwards through which technology became a highly specialised and divided activity. Everyday life became filled with vast numbers of different technical artefacts, the products of industrial processes which in their entirety receded from view. Indeed, 'modern' technology is industrial technology, and many theories and analyses of technology in society operate within the frames that are being set by industrial technology. It sets the background upon which 'technology' is often interpreted (Simondon, 2016; Rip, 2012; Feenberg, 2010; Geels, 2005; Ropohl, 1999; Beck, 1997; Latour, 1993; Hughes, 1983; Noble, 1977; Marx, 1976; Mumford, 1970). On the other hand, for some time, novel, complex and often messy ways of the production of technology and knowledge have been unfolding in between and beyond the established 'modern' settings, such as corporations or universities (Latour, 2013; Knorr-Cetina, 2007; Irwin and Michael, 2003; Funtowicz and Ravetz, 1993). There is a need to think and address these novel arrangements and the novel epistemic and technical processes that they enable. Open digital fabrication is one of them, yet by far the only one. To understand and analyse such novel processes in which technical objects and social arrangements show dynamics and circulations that transcend the wisdom gained from an observation of industrial technology we need appropriate concepts.

With TechKnowledgy I want to rediscover and update the older meaning of technology, mentioned by Jasanoff above, that foregrounds technological processes instead of their products[1]. When we study technical skills, a form of knowledge, we also need to ask what are the processes that regulate, produce and organise such skills and their acquisition? What are the processes through which technical skills are studied and passed on? And how are particular technical objects an inextricable part of such processes and transformed through them? What are the processes through which technical objects are produced? In short, how are the becomings of technology and knowledge produced and organised together? [2]

In the introductory chapter, I defined a TechKnowledgy as a historically emergent and dynamic set of collective procedures that produce and organise technology and knowledge. This chapter sets out to give this definition the substance needed to arrive at a sufficiently complex concept for the analysis of phenomena like open digital fabrication. A look back at the word's history already provides some important insights. The term 'techknowledgy'[3] was coined in literature on 'knowledge management' in management and organisation studies. It has been used there, however, to designate ICT applications that store and transmit knowledge within an organization, such as a wiki or a mailing list (Davenport and Prusak, 1998; Davenport, 1996). It is significant that the term was coined when digital information technologies made the constructed nature of knowledge evident again and turned it into a digitally malleable relation. My usage of the term transcends this narrow meaning, yet 'knowledge management' also hints at an important aspect, namely that knowledge and technology are both 'managed', consciously produced and organised.

The following theoretical discussion, however, will first problematise the notions 'technology', 'knowledge', 'production' and 'organisation' to be able to arrive at a conceptual level where they can be thought of as integrated in complex processes. The first parts of the chapter, which discuss 'technology' and 'knowledge', draw on theories from different fields such as the philosophy of technology, anthropology and the sociology of knowledge. The second part, which takes on 'production' and 'organisation', is strongly based upon the machinic thinking of Gilles Deleuze and Félix Guattari (Deleuze and Guattari, 2004), whose concept of machinic assemblages provides a fruitful way to think and analyse dynamic processes of producing and organising heterogeneous elements such as the entwined becoming of technical objects and human subjects. Two brief digressions on industrial engineering and technoscientific myths complement the theory by linking it to two phenomena that highlight important aspects of TechKnowledgies. The digressions are visually highlighted as they divert from the general theoretical discussion and complement it with transversal arguments. The chapter ends with an outlook on the analytical perspectives and strategies of the empirical case studies.

2.1 Technology: technical objects

To prepare the ground for an understanding of technology adequate to TechKnowledgy, I go through four different conceptions of 'technology' in a simplified manner. There are many different ways in which technology is understood in academia and while none is right or wrong, they point out different aspects of what

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1 In German, some authors distinguish 'Technik', designating technical artefacts and their use, from 'Technologie', designating the scientific knowledge on the design of technical artefacts (Ropohl, 1999, 2009). In the English language, no such distinction exists.

2 The prominent heuristics for innovation processes of the multi-level-perspective (Smith et al., 2010; Geels, 2005), for example, stops at the observation that different elements work together, or not, at different levels. Its guiding difference is that between 'new' and 'old,' which leads to a heuristics of general patterns of various innovation processes. This, however, does not see the many different ways in which particular complexes are being put together to create 'sociotechnical' change.

3 The term has also been used to refer to universities by Böhm (2002), a usage closer to mine. Also an edited book with texts by humanities scholars is entitled 'TechKnowledgies' (Yablonsky, 2007) to designate interdisciplinary interpretations of novel technical dynamics.

might be considered technology[4]. There may be more, but the mentioned understandings paint a sufficiently broad picture from which to continue. On their own, however, each of these four are problematic for getting to grips with the plurality of technologies.

First, there is the classical idea that technology is the sum of the material stuff people use to achieve particular ends. Technology is found in the tools humanity has invented. Technology is 'instrumental' it is said from this perspective. Search for an end and an artefact as a means and you have found technology. While on a very general and abstract level this may be true, this conception of technology takes the hand axe as the prototype for all other technology and is unable to see the differences between hand axes and nuclear power plants. An even more reductionist understanding of technology, derived from this one, even leaves the means-ends logic out and equates technology merely with technical objects. This, however, even forgets that a hammer is only a technical object within a process such as nailing. Second, there is an understanding where everything is 'technical' that is based on routines and a means-ends logic, yet the means do not need to be artefacts. In this view there can be learning techniques, yoga techniques, communication techniques and so on. Most famously, Max Weber argued for such a wide notion of technology. While I am sympathetic to the idea that technology is found in a particular principle of action and not necessarily in objects, I also think that from a sociological point of view it is of little help to see every routinised action as technology. Otherwise, we would not have a good way to distinguish a massage from paving a road.

Besides these two understandings of technology, which take individual actions as the primary element where technology is found, there is a third understanding that has become popular within STS. This understanding holds that for there to be technology there needs to be a relation to something else. Instead of 'technology' we find 'sociotechnical systems' (Ropohl, 1999; Hughes, 1983) or 'actor-networks' (Latour, 2005), that is, different technical objects in particular social contexts. A technical artefact, in this view, can only be something if it is part of a complex of relations to social practices, organisations, norms and so on. Then we see that a hand axe is also an 'actant' (cf. Latour, 2005) which co-configures its user and affords particular actions or that a nuclear power plant can only operate if it is part of a larger 'system' of electricity generation and consumption where vast amounts of different kinds of work and coordination are necessary to keep this operating. While TechKnowledgy draws much inspiration from this line of thought, I see two related problems in it. First, the argument that we need to focus on the relations between heterogeneous entities sits on the presumption that 'the social' and 'the technical' are separate to be able to connect them – actor network theory mainly uses the terms 'human' and 'non-human' to then create connections. Second, and related, often research on these lines is satisfied with showing that heterogeneous things actually belong together, that there is 'matter' in 'the social'. However, this mostly does not tell us much about technology; instead, often a simplistic understanding of technology which thinks of technical artefacts (see above) is used in such relational thinking. The strength, however, of this line of reasoning is that it reminds us that to be able to have and to use technology many more things need to be in place and work together and connect. With such a complex[5] understanding of technology we eventually have the cognitive means to capture the differences of hand axes and nuclear power plants.

There is a fourth understanding of technology, which considers it to be a medium that enables and shapes how people perceive and act in the world. Etymologically, considering something to be a medium means considering it to be 'in the middle', as something that mediates. Marshall McLuhan, one of the founders of media theory, succinctly put his thoughts on media in his famous slogan 'the medium is the message' (McLuhan, 1964). Instead of the content, for example of television, from soap operas to war documentaries, the major influence on how society entwines with this technology and changes is the way in which this

[4] Particularly helpful for me to distinguish these four understandings have been: Lösch, 2012; Grunwald and Julliard, 2007; Degele, 2002; Achterhuis, 2001; Hubig et al., 2000; Ropohl, 1999.

[5] 'Complex' designates that which belongs together (Morin, 2008).

content is being produced, circulated, controlled and formed by the medium of television and the social structures that interact with it. For McLuhan, media are form-giving milieus within which particular messages, interactions and communications take place and which, thus, configure how the world is perceived, construed and acted in (cf. Grampp, 2011, chap. 2.3). They create whole environments that channel action and thought, and they do so in an ecology of milieus that have to be seen in relation to each other. Considering technologies to be media is one of the strongest ways to counter the idea that technical artefacts are neutral means. Rather, from this perspective there are hardly any means outside of technically mediated perceptions and actions (Gamm, 1998). Technological arrangements influence how people perceive, act upon and interpret the world and how knowledge is made explicit and transmitted. Hence, they also shape subjectivities and socialities. Particularly through digital media technologies this perspective on technologies is becoming more important and well-known (Serres, 2015; Hörl, 2013a; Stiegler, 2010; Flusser, 1999) it is, however, not confined to these. Streets, buildings and simple tools such as hammers within their respective arrangements can also be seen as media.

There may be more understandings of technology, and one could discuss many more aspects within these four understandings sketched above. Actually, all four – except the reductionistic version that equates artefacts with technology – are important elements in TechKnowledgy. There is one more hindrance in many typical understandings of technology, however. They typically start their thinking with realised technologies – the hand axe in use, the skill possessed by someone or the sociotechnical system of the nuclear power plant. And actually such an understanding of technology as things ready to be used is stabilised within industrialised economies and technologised societies where people encounter vast amounts of ready-made technical stuff to be bought and then used. Also in academic discourse we find more studies of particular artefacts in use than we find studies about the imagination, creation, design and experimentation with artefacts in becoming. With notable exceptions (e.g., Rip, 2009), there are few studies that take the 'process of technology' as their starting point and not particular products of this process, i.e. artefacts. TechKnowledgy, however, is a process concept. To consider the process of technology the work of Gilbert Simondon, to which I turn now, is particularly significant.

In 1958 Simondon (2010, 2012, 2016)[6] published his PhD 'On the mode of existence of technical objects' and proposed a theory of technology which was strongly inspired by evolutionary theory, information theory and cybernetics. In this work, he was at pains to argue that technology is part of human culture and human history and tried to resist anti-technical resentments that he saw as defining for mainstream culture at that time. He argued that large cultural changes are entwined with changes in technical objects and in the relations between humans and such objects. Accordingly, modern society would have to change strongly in its perception, evaluation and organisation of technology to enable new modes of becoming of technology. Through this, Simondon thought, potentials for technical and human becoming – which in his theory are entwined – could be fully liberated and people would no longer perceive technology as 'the other' or as alienating. Simondon's thinking about technology is, therefore, linked to a wider theory of 'individuation', which is interested in the processes in and through which entities – technical objects, humans, socialities – become individuals and how they change. The theory of technology he puts forward is also a theory of subjects and societies in which he 'asserts the primacy of ontogenesis, a primacy of processes of becoming over the states of being through which they pass' (Massumi, 2009, p. 37). But let's focus on technical objects first, which in Simondon's thought require a temporal conception.

[6] This theory is currently being rediscovered. Simondon had a huge impact on Gilles Deleuze's work, which has been becoming more and more prominent in some parts of sociology, STS and anthropology and which is also central to this chapter. Some recent writers on technology draw directly on Simondon, e.g. Hörl (2013b), Stiegler (2010) and Latour (2013). Indeed, this is not surprising, since Simondon's work addresses many contemporary desiderata such as overcoming simple dichotomies such as nature vs. culture and thinking in more relational and processual terms.

> '[I]nstead of starting from the individuality of the technical object or even from its specifity, which is quite unstable, it is preferable to reverse the problem […] the individual technical object is not a datum of the here and now […] but something that has a genesis. The unity of the technical object, its individuality, and its specificity, are consistent and convergent characteristics of its genesis. The genesis of the technical object is part of its being. The technical object is something that does not exist prior to its becoming, but that is present at every stage of that becoming; the technical object is a unit of becoming' (Simondon, 2010, pp. 6–7).

Considering a technical object, e.g. a laptop, requires us to consider the 'evolutionary line' of which it is a part, in which there are also typewriters or early personal computers and from which elements can be found in the laptop. Furthermore, there are potentials of the laptop to link into other technical objects, e.g. a new software program or a network, to form something new. The laptop might even be installed in a car to work as its on-board computer. Besides such a plurality of technical objects that work together or can be assembled into new objects, there are corresponding social practices, which entwine with technical becoming. In practices of imagination, design, creation, assembly, maintenance, transformation and ongoing mixtures of these, people entwine with technical objects and can make use of their technical potentials or even turn them into something else, if the object 'cooperates'. In this process view of technology all of this is part of technical reality. What defines technology for Simondon is not simply the object such as the laptop but the process that formed and transforms the laptop, in which technical objects play a vital part. A technical object in a way 'stores' human capabilities or human achievements of the past that can be built upon to create novelty. It is in this sense that Simondon argues that technical objects are part of human history.

The analyst of technology, therefore, also needs to think about the spaces, times and socialities in and through which technical practices are organised. In the industrial society of Simondon's time, there were – and continue to be – strong and visible differences, stabilised through particular divisions of labour, between these technical practices. Simondon argued that people and organisations are only in premature contact with technical reality if they only encounter parts of this process instead of its entirety. Workers in the factory, Simondon argued in extending Marx, are alienated not simply because they do not own the machines but even more so because they only operate the machine and are excluded from inventing, designing, transforming and setting the purposes of machines. Through such examples and arguments Simondon unfolds his complex theory of the entanglement of human and technical becoming. 'Society' and 'technology' in this view need to be thought of as complex 'ensembles'[7] (a term Simondon regularly uses) of technical objects, people and organisations. Together they constitute processes of becoming in which they take part and can be arranged quite differently.

In a central text of his later work, Simondon (2009) claims that the history of modernity has seen at least three grand changes in the constellations of people, knowledge and technical objects. Each of these object-historical changes, however, entwined with huge changes in societies and cultures and established and stabilised particular ways in which technology is being unfolded. In pre-industrial technical regimes, craftsmanship was the dominant mode to work on and with technology as tools. Energy and information was provided by the craftsman, and the construction of technical objects and their use was rather closely linked and artisans knew the users of their tools[8]. However, when machines made the industrial mode of production the dominant regime for technical realities, the constellations changed dramatically. The more complex

[7] Already at this point I want to mention that Simondon's theory of individuation and his thinking in heterogeneous ensembles was taken up by Gilles Deleuze and proved to be central to the latter's work, which will become central when I discuss the 'organising' and 'producing' aspects of TechKnowledgy. Thinking in ensembles is one step towards thinking in assemblages.

[8] This seeming 'unity' is the reason for the romanticised nostalgia for craftsmanship, that can still be found in academia (e.g. Sennett, 2008) and in some strands of discourses about the maker movement, where the maker is seen as someone producing technology in self-sufficient ways.

division of labour split invention, construction, use, maintenance and transformation of technology apart between different individuals and groups. Technical reality became divided.

However, Simondon hinted at a third shift and the emergence of ‘post-industrial’ realities, which he linked to the appearance and unfolding of open objects[9]. These open objects partly transgress the industrial boundaries between creation, production and use, in that they are partly indeterminate and changing outside or beyond particular industrial divisions of labour in Simondon’s time. In his 1958 study, Simondon already speaks of novel ‘open machines’ and technical ensembles that share growing margins of indeterminacy. He develops the idea of ‘open objects’ further in a text written around 1970 and published for the first time in 2006[10]. The text is about the emergence of novel networks of technical objects that entwine with a new cultural formation Simondon saw partly developing, the ‘technical mentality’: ‘[I]n order for an object to allow for the development of the technical mentality and to be chosen by it, the object itself needs to be of a reticular structure [...] an *open object* that can be completed, improved, maintained in the state of perpetual actuality’ (Simondon, 2009, p. 24, italics in original).

It is the combination of objects into networks and the corresponding culture of changing these technical objects and their relations that Simondon focuses on. Simondon’s examples of such ‘multifunctional network[s]’ (2009, p. 22) are communications and energy networks as infrastructures for open objects[11]. Into the electricity network one can plug different machines, for example, and without changing the whole network one can change the machine which serves an individual purpose yet is still part of the network. For such linking of objects to networks, however, standardisation is a prerequisite. Open objects need connectivity, the possibility to be connected. Simondon thus sketches and speculates about open objects that are flexible on the individual level due to their connectedness to stable networks and that are malleable and changeable due to standardised parts out of which they are partly made. Central to open objects is the indeterminacy, the malleability and the multifunctionality of these objects. In addition to the technical characteristics of objects, Simondon argues that there needs to be a culture of changing technical reality, he calls ‘technical mentality’. The latter corresponds with people who somehow participate in all ideal typical stages of the technical process: imagination, invention, design, production, use, maintenance and transformation.

> ‘If one seeks the sign of the perfection of the technical mentality, one can unite in a single criterion the manifestation of cognitive schemas, affective modalities, and norms of action: that of the opening; technical reality lends itself remarkably well to being continued, completed, perfected, extended’ (Simondon, 2009, p. 24, italics in original).

Simondon saw the technical mentality as being a subtle tendency in culture and he was afraid that it could not further develop. For open objects the ‘technical relation’ to other objects is at least as important as their ‘economic’[12] relation to markets or ‘social’ relation to people. Each of the three according to Simondon can

9 Flusser, in a similar threefold argumentation, saw the coming age of the ‘robot’ after the age of the tool and the age of the machine. In this age, humans and robots co-function together. ‘Thanks to robots, everyone will be linked to everyone else everywhere and all the time by reversible cable, and via these cables (as well as the robots) they will turn to use everything available to be turned into something and thus turned into account.’ Accordingly, in the ‘factories of the future’, Flusser writes, ‘manufacturing means the same thing as learning – i.e. acquiring, producing and passing on information’ (Flusser, 1999, pp. 48, 50).

10 The text first appeared in French, in 2009 in English (Simondon, 2009) and in 2011 in German (Hörl, 2011). It is a central piece of Simondon’s thought.

11 Of course, there are all kinds of other examples. Electrical instruments come to my mind, where it is part of the music culture to change the sounds due to varying constellations of instruments, effects, amplifiers and so on. Simondon (2009) even argues that buildings designed in such a way that they can be constantly reconfigured express the technical mentality.

12 Marx already thought of such a dual nature of objects (as commodities): they have use value and exchange value. The latter, Marx claimed, was of prime importance in capitalism. And he was proven right: most objects that we face in mundane life are produced for the sake of profit, leading to now well-known effects such as obsolescence. Even the social sciences followed the spirit of capitalism and tended to mainly see objects as commodities (e.g. Appadurai, 1986).

create hindrances to more objects becoming ‘open’, that is transformable, connectable, unfolding and indeterminate. The processes that organise technical becoming, we learned from Simondon, are entwined with object-historical changes that transform what ‘technology’ is. The next section discusses what this tells us about ‘knowledge’ in relation to technology and its contemporary transformations.

2.2 Knowledge: relations

Technical knowledge may sound straightforward. That is the knowledge of how to tighten screws and repair cars, one might think. While this is not wrong, it is insufficient when we think about technology in becoming, because then we also need to think about knowledge in becoming, that is creativity, learning, education and transmission of knowledge. This entails that one also considers the social organisation of knowledge, which is also the organisation of what and how human beings as part of society become. Thus, the discussion of ‘knowledge’ suitable for TechKnowledgy needs to be rather fundamental and cannot start by saying that ‘technical experts’ have ‘technical knowledge’. Rather, we have to tackle the question of how human beings and knowledge become, and this will show that ‘knowledge’ is a plural category (Maasen, 2009). This task is not made easier by the fact that knowledge, what it is, how it is produced and acquired, stored, transmitted and so on changes in history, and technology has a huge part to play in this (Ingold, 2011; Morin and Kern, 1999; Latour, 1993). Many scholars have turned to how ‘knowledge’ is currently vastly changing due to digital media (Serres, 2015; Hörl, 2013b; Neuser, 2013; Stiegler, 2010; Debray, 2007). I briefly discuss one example to show demands that the following discussion on how to analyse ‘knowledge’ in TechKnowledgies needs to come up to.

The German philosopher Neuser (2013) argues that digital technologies drastically change what knowledge is, how it is interpreted, legitimated and governed. Modernity, he argues, for centuries was based on the idea that the ‘subject’ is the foundation of knowledge. Modern epistemology dealt with the question of what the subject can and cannot know and modern society built its institutions that way. In schools pupils are tested for what they have ‘in their heads’, academic careers are based on individual publications or patents are given to entrepreneurs that are seen as the source of an invention. Yet, in times when thousands of Wikipedia articles are written by software programs, Neuser argues that the modern conception of an autonomous subject is no longer a suitable foundation for knowledge. Contemporary subjects participate in vast sociotechnical knowledge networks, where they are not the prime reason for new knowledge but simply a part. Therefore, the old knowledge regime of modernity – based on the idea of the subject as the foundation of knowledge – is collapsing, and ways to deal with novel forms of knowledge, which is founded in networks of humans and digital machines, have yet to be found. This is somewhat similar, yet with another twist, to the by now classical argument of Latour (1993) that the modern ‘purification’ is no longer working due to the dramatic ‘hybrids’ of things and people and natures that have been emerging.

What does this imply for an analysis of contemporary technical knowledge? First, we need a relational ontology of knowledge and the ways in which such relations are established. And this entails relations to people, organisations and objects. For these purposes, first, the environmental anthropology of Ingold (2011) that focuses on human becoming in entanglement with dynamic environments is discussed. Then, second, I turn to Collins’s (2010) work on tacit and explicit knowledge, a fundamental distinction to understand how different forms of knowledge are distributed over different entities. This is central to understand technically mediated knowledge. Third, I discuss how technical knowledge needs a socialised understanding that addresses how it is legitimated, organised and entwined with interpretive frames and meanings.

I start the discussion by drawing on the environmental anthropology of Tim Ingold. There are many offers for relational concepts of knowledge by now, including ANT. But Ingold’s work, which is influenced by

Simondon and Deleuze, is particularly suitable and insightful for the task at hand, since it focuses on processes of becoming. Central to Ingold's diverse work is his thinking of the complex of organism/environment. He is interested in how human beings co-become with their surroundings and what this tells us about human life. This process thinking is also influenced by Marx, who has already asked how human beings produce themselves through their activities; human beings are rather 'human becomings'[13]. Ingold's understanding of knowledge is thoroughly process- and practice-based in which he

> 'prioritise[s] the practice of knowing over the property of knowledge. Rather than supposing that people apply their knowledge in practice, we would be more inclined to say that they know by way of their practice (Ingold and Kurttila 2000: 191–192) – that is, through an ongoing engagement, in perception and action, with the constituents of their environment. Thus, far from being copied, ready-made, into the mind in advance of its encounter with the world, knowledge is perpetually "under construction" within the field of relations established through the immersion of the actor–perceiver in a certain environmental context' (Ingold, 2011, p. 159).

Experience, which according to Ingold is based on movement, is crucial for all human knowledge and knowledge cannot be separated from individual human beings and their lives. Ingold's writing is close to the tradition of phenomenology when he states: 'To know things you have to grow into them, and let them grow in you, so that they become a part of who you are' (Ingold, 2013, p. 1). Knowledge in a book, for example, has to be constructed in the practice of reading it. Of course, human beings participate in collective and social knowledge, yet learning this takes place in individual lives in 'correspondence' (Ingold, 2013) with dynamic and changing environments. Ingold thinks of humans (and other organisms) as 'lines' that move and unfold throughout their lives, entwine with other lines and through this become. Correspondence, however, is more than a co-presence. Correspondence takes place when someone enters a dynamic relationship with someone else or with things in which different lines 'answer' to each other. Relatedly, Ingold takes the whole organism as the knowing entity. Knowledge is not only the mental models and cognitive processes of people but all of the organism's capacities for movement, feeling, perception, communication, action, interpretation and so on. Although Ingold conceives of all of this as belonging together, for purposes of an analytical concept I disentangle this by discussing tacit and explicit knowledge to address the ways in which knowledge spreads to different parts of the organism and environment.

For Collins (2010), the leading expert on tacit and explicit knowledge, knowledge similarly entails all abilities of the human body and brain. However, he distinguishes knowledge that can be explicated into a medium and taken up by another human or a machine from tacit knowledge which cannot or is not (yet) explicated. In his detailed analysis of tacit and explicit knowledge he argues that they both belong together – one cannot be without the other and they are the two dimensions that create human knowledge. Writing a book for example is to explicate knowledge in the medium of written language, and reading the book is to learn and to interpret this knowledge. Reading and writing, however, depend on tacit knowledge such as the ability to use language correctly and possessing collective cultural frames of interpretation. Software code is another medium for explicit knowledge, which instructs machines to do particular things and transfers abilities to machines. The machine, however, does not possess tacit knowledge, yet its constructor needed tacit knowledge to build it. Therefore, although artefacts are crucial for the different forms of explication, transmission of explicit knowledge and reproduction of particular aspects of explicit knowledge 'it remains the case that, in the last resort, humans are the only knowers' (Collins, 2010, p. 6) since they are capable of handling and unfolding explicit and tacit knowledge. The distinction between explicit and tacit knowledge is fundamentally important in analysing technical practices since working with technical objects

[13] The Marxist philosopher Ernst Bloch (1995) places the becoming of human life in the centre of his process philosophy, which states that all of reality becomes into that which it is 'not-yet'.

always entails the active coordination of explicit and tacit knowledge. For open-source practices this is especially significant since the core practice of sharing knowledge online depends on the affordances of digital media to explicate knowledge. Furthermore, discourses on an 'open' knowledge regime overly focus on an increase in explicit knowledge. However, without tacit knowledge the digitised explicit knowledge cannot 'come to life'.

Collins distinguishes three categories of tacit knowledge that are important to know as an analyst. First, there is 'relational tacit knowledge', which might or might not be explicated due to social relations. Particular knowledge is intended to remain secret (e.g. within companies that want to protect their 'intellectual property') or people are differently educated, and some knowledge remains inaccessible to them. Relational tacit knowledge could in principle be explicated, yet for social reasons it is only explicitly shared with a selected few or no one. Second, there is 'somatic tacit knowledge', which remains tacit due to reasons of the human brain and body. You can write an instruction of how to ride a bike, for example, but the learner has to actually do the riding to learn. Third, 'collective tacit knowledge' is held by social collectives. It designates practices, norms, morals, interpretive frames, collective imaginaries and so on. This cannot (yet?) be explicated since it is an emergent effect of society, and individuals acquire it through participating in it, which is typically called socialisation. Gaining new knowledge, i.e. learning, typically involves all these dimensions of explicit and tacit knowledge. As an analyst of TechKnowledgy, which is much about learning, one has to be aware of the ways in which translations between explicit and tacit forms of knowledge are being enabled and organised. Who is enabled to correspond with what kind of technical knowledge, and how does this happen? What are the organisational forms that enable exchanges between 'learners', 'educators' and technical objects? Furthermore, what are the norms, imaginaries and practices that are being entwined with which kind of technological setting?

From this general discussion of human knowledge I turn to technical knowledge in particular. Discussing Simondon above, I showed how technical knowledge is not simply the practical knowledge of modifying artefacts. Instead, it is as multifaceted as the technical process, including aspects of imagination, invention, design, production, transformation and so on. In his study on 'making', Ingold (2013) showed in great detail how makers[14] and their artefacts correspond and together form the technical outcome. 'Making […] is a process of correspondence: not the imposition of preconceived form on raw material substance, but the drawing out or bringing forth of potentials immanent in a world of becoming' (Ingold, 2013, p. 31). In a process artefact and maker mutually inform one another and co-become. Ingold, like Simondon, is a sharp critic of the idea of 'hylomorphism', which holds that humans conceive form and novelty and impose it onto a passive world of objects. Instead, Ingold's idea of correspondence argues for multiple causalities that are involved in the creative process of which humans are but one. Through correspondence different elements with particular potentials are entwined in a process from which novelty (a technical invention) and form (a technical function) emerge. Therefore, technical knowledge needs to be thought of as an emergent effect of intense relations of cognitive and bodily engagement between people and objects.

However, technical activities do not simply take place in the open, but as Simondon already argued, are socially organised. Ingold and Collins point out how the knowledge of making things or of explicating knowledge is social knowledge as well, a knowledge of how to relate to the world and to others. There is, in addition to technical knowledge of making, a social knowledge about the organisational forms, practices and narratives that entwine with technical practices. This gives meaning to technological artefacts in society and the ways in which their becoming is organised. This is also a knowledge of the politics of technology and the evaluation of different technologies and technical settings. Taking this line of thought even further, we need to think of technical artefacts as mediators between people, e.g. between developers and users,

[14] Ingold has any form of human making in mind and not the particular group that receives so much attention lately and is related to open digital fabrication.

producers and customers (e.g. Flusser, 1999). Creating, unfolding, producing and changing technology is, therefore, also to change or to stabilise social relations (Stiegler, 2014).

As a way to sum up the discussion so far I turn to the example of ‘industrial engineering’ as an ideal type of a TechKnowledgy. This shall open the path for the discussion of machinic thinking and the ‘organising’ aspect of TechKnowledgies.

The TechKnowledgy of industrial engineering

One of the most influential TechKnowledgies in contemporary societies is industrial engineering. It is important to understand right at the beginning that industrial engineering is not simply ‘capitalist technology’. Rather, it is a special way of producing and organising technology and knowledge in capitalism, and there are others within it as well. But industrial engineering has stabilised industrial capitalism, which even today is still significant to most material technologies in modern societies. For many observers, industrial engineering might just be the normal way in which modern technology can be unfolded. However, industrial engineering was not a bare necessity or a simple ‘co-evolution’ of modern technology and social organisation. Rather, as the historian David Noble (1977) shows in an excellent study, industrial engineering was collectively ‘designed’ over decades around the turn of the 19th and 20th centuries by the leading classes and networks of industrial, financial, political and educational elites. Noble understands industrial engineering not simply as an activity done inside a firm but as a ‘technology for social production’ that is based on a complex arrangement of different elements. This analysis is based on Marx and Mumford, two theorists, who I will discuss below since their perspectives are central for a complex understanding of TechKnowledgy. Noble’s study can be seen as a brilliant analysis of a TechKnowledgy. For that matter I discuss this historical example in some length.

With great attention to detail and covering materials from industry, science and education, Noble analyses the emergence of the modern engineer as a social figure that connects science and industry. The creation of modern engineering is entwined with the rise of industrial capitalism. This process also shaped the arrangements of technical creation and work that in turn defined industrial processes. Noble, thus, pursues a thoroughly socialised theory of technology, in which humans are central elements as well, and conceives of technology in ways that I discuss below as ‘collective machines’:

‘Like every other social process, technology is alive. People—particular people in particular places, times, and social contexts—are both the creators of modern technology and the living material of which it is made. Designers and builders of an ever more sophisticated productive apparatus, they are at the same time the critical constituents of that apparatus, without which it could not function. The corporate engineers of science-based industry [...] strove to achieve the necessary production and organization of not merely the material elements of modern technology but the human elements as well’ (Noble, 1977, p. 167).

The organisation of human and material elements is traced by Noble in ‘the rise of science-based industry’, ‘the emergence of the professional engineer’, ‘patent-law reform’, the ‘industrialisation’ of higher education and the establishment of novel disciplines – nowadays called technoscience – as well as the emergence of modern management and its results in employee organisation, e.g. through Taylorism. Noble covers the change of entrepreneurial invention into an organised field of innovation in networks of industry and science, institutional changes that affected universities and laws, as well as the divisions of labour within firms that separate intellectual and manual labour, with engineers working on the intellectual side of technology. Through this, Noble shows, however, that instead of individual engineers it is the corporations, which were able to bring the products and the processes of technical creativity under their control, which benefit from this social change. They are the centres of processes which use educated engineers as materials and tightly enforce a double standard of technical production: technical *progress and profit must be ensured and the arrangements within which modern engineering is reproduced are paying attention to this.*

There are, however, two aspects that I want to add to Noble's analysis, which remains largely silent on technical objects and workers and consumers. Actually, the technical objects of industry are being conceived and produced in ensembles of large machinery, which often demand much effort of engineering as well and contribute as the fixed capital of corporations to their relative power concerning the technical processes. Furthermore, besides divisions of labour, industrial engineering also entails relations to and conceptions of consumers of its products. Stiegler (2010, 2014), in an extension of Simondon's ideas, has criticised the effects on knowledge that industrial principles have on consumers, i.e. almost everyone. Due to the only partial involvement in the becoming of technical objects, people are deprived of knowledge on how to make things (from cooking to desiring and inventing their own livelihoods) and of knowledge on how to live and coordinate with others. While Stiegler paints his critique with a very broad brush, he unveils tendencies of the becoming (or unbecoming) of knowledge in industrial societies, and located within these tendencies there also operates the TechKnowledgy of industrial engineering.

Nowadays, many industrial companies look different from their predecessors, at least in the 'rich north'. Furthermore, industries have been transforming, many aspects of value chains have been 'outsourced', networks of firms are becoming more important, and along with digitisation some firms use formats of 'open innovation' to include crowds in technical creativity (Meyer, 2016; Urry, 2014; Chesbrough, 2003; Castells, 2002). Yet, considering its fundamental structures and the networks of the important institutions for its reproduction, such as universities and companies, industrial engineering is mainly similar. The TechKnowledgy has further evolved and diversified, with more 'disciplinary' branches, novel forms of management and more diverse career paths. But considering fundamental divisions of labour, corporate monopolisations (at least attempts to do so) of the products and core processes of technical creativity (Mirowski, 2011) and the role of engineers as media between science and industry the same structures apply.

Seen from the above-discussed theories, the technical objects in the TechKnowledgy of industrial engineering disappear as a bare necessity. Rather their becoming is organised in a particular way, which also has an impact on the possible shapes and trajectories of these objects. The TechKnowledgy, therefore, produces objects which are invented, designed and modified by engineers as part of corporations, produced by factory workers and bought and used by consumers. The splits of the technical process, criticised by Simondon, are obvious here. We also see that these objects are not only transformed by particular engineering practices but that these practices themselves are entwined with economic arrangements and power structures of industrial societies. Thinking about knowledge in this TechKnowledgy, we see it concentrated in the social group of engineers and also in the corporations that enable collective engineering practices and the tacit knowledge transfer necessary for it. The corporations also typically hold a legally enforced monopoly for the explicit knowledge (patents etc.). The becoming of technical knowledge – in implicit and explicit forms – is entwined with the becoming of engineers, who through their socialisation are being endowed and stabilised as a group with particular technical expertise. Engineers, in fact, are being 'produced' by this TechKnowledgy in universities and firms, and their social status as 'experts' is being legitimated through it. Furthermore, industrial engineering is located within industrial capitalism and its hegemonies. There are particular cultural conceptions and legitimisations of this form of technical becoming, including a conception of 'industrial technology' or sometimes even 'high-tech' and its benefit for modern societies. Besides being a means to sustain profit, industrial engineering is being legitimated and implicated in particular ways of life and social organisation, a particular societal model.

2.3 Machinic assemblages: producing and organizing

A TechKnowledgy is produced and organised, however what does this mean? Thinking through this from within industrial engineering one might say that a firm produces and organises technical creativity. Actually most sociological organisation research and theory would say something similar as well, with its focus typically being individual organisations, a company, a hospital or a school, although there is a recent shift from entities towards processes of organising (e.g. Scott, 2004). Such processes of organising, when seen beyond individual situations or organisations, have become tremendously complex, especially in relation to contemporary technology. Not only have technical and other objects become highly mobile and connected but most social life finds itself in a 'global', highly dynamic world with often rapid and spontaneous change. This, however, is not a world of complete chaos but also of dynamic forms of order which need to be grasped in new ways that transcend classical sociological wisdom and need novel epistemologies and ontologies of social life. Many contemporary thinkers have emphasised this (Therborn, 2011; Walby, 2009; Adam and Groves, 2007; Urry, 2007; Bauman, 2000; Beck, 1997; Latour, 1993).

Related to these problems, the concept of 'machinic assemblage'[15] as elaborated in the work of Deleuze and Guattari has been rediscovered recently. It is particularly suitable to grasp heterogeneity and multiplicity, flows and movements and processes of transformation, adaptation and becoming of the complexes that are the products and producers of processes of organising. These processes may entail particular individual organisations, yet cannot be reduced to them. In the following, after setting out the contours of machinic thought, I discuss theories by Marx, Mumford and Foucault that were influential for Deleuze and Guattari in defining their notion of machinic assemblage. I end the contextualisation of machinic thought with a comparison to ANT. The chapter does not intend to disconnect ANT and machinic thought, but aims to gain sensibilities and ideas that are articulated in the latter and its predecessors. In particular this aims to regain the machinic aspects of the theory. Many contemporary writers under the influence of ANT reduce 'machinic assemblages' to mere conglomerations of different elements, to the 'assemblage'. This tends to overlook, however, that Deleuze and Guattari's theory was intended to grasp the particular productive qualities of assemblages, the machinic productions that unfold them in particular ways. This is the main reason why I use the notions machinic assemblage or collective machine and not only assemblage.

To get into machinic thinking one needs to understand that the notion 'machine' that is used here is far removed from the typical usage of the term for artefacts that convert energy. 'Common usage suggests that we speak of the machine as a subset of technology. We should, however, consider the problematic of technology as dependent on machines, and not the inverse. The machine would become the prerequisite for technology rather than its expression' (Guattari, 1995, p. 33). In the thinking of Deleuze and Guattari and the ontology that they argue for '[e]verything is a machine' (Deleuze and Guattari, 1994, p. 2):

> 'It is at work everywhere, functioning smoothly at times, at other times in fits and starts. It breathes, it heats, it eats. It shits and fucks. What a mistake to have ever said the id. Everywhere it is machines—real ones, not figurative ones: machines driving other machines, machines being driven by other machines, with all the necessary couplings and connections. An organ-machine is plugged into an energy-source-machine: the one produces a flow that the other interrupts. The breast is a machine that produces milk, and the mouth is a machine coupled to it. The mouth of the anorexic wavers between several functions: its possessor is

[15] Good introductions to machinic thinking, without the sometimes difficult writing style of the two philosophers, are Raunig (2010) and Hubatschke (2015). For a general introduction into assemblage theory DeLanda's work is a good start (2006). A short introduction is given by Livesey (2010). A good overview of the different ways in which assemblage has been used in social science is Anderson et al. (2012). Other interesting takes on assemblage exist as well (Acuto and Curtis, 2013; Harman, 2013; Legg, 2011; Rabinow, 2011).

> uncertain as to whether it is an eating-machine, an anal machine, a talking-machine, or a breathing machine (asthma attacks)' (Deleuze and Guattari, 1994, p. 1).

From this example, which draws on the machine mother-child, itself constituted by smaller machines, one can already see that the interest in machinic thinking lies not on individual 'parts' but on constellations of machines, in how they work together, how connections produce and interrupt flows, how there is change through 'assembling' a machine from other machines. In Simondon's theory of technology, which sees technical becoming in the combination of technical objects, already lies an ontological pillar that is used by Deleuze and Guattari to think becoming everywhere: in nature, in animals, in humans, in societies. Similar to Simondon they are more interested in the processes that constitute and transform entities than in individual entities on their own.

Machinic thinking is based on a technomorphic[16] understanding of reality in which 'everything is production: production of productions, of actions and of passions; productions of recording processes, of distributions and of co-ordinates that serve as points of reference; productions of consumptions, of sensual pleasures, of anxieties, and of pain' (Deleuze and Guattari, 1994, p. 4). While Marx's influence is visible here in the emphasis on production, the productions that the philosophers ascribe to their machines are not modelled on industrial processes or mechanistic ideas of technology and social order that might be associated with them. Production is also not seen as a planned process with determined outcomes. In machinic thinking machines are modelled rather more like experimental technological processes, that connect and mix and try different components, can fail and break apart or generate novelty. Machines and their elements have to be conceived as becoming and, therefore, constantly producing. Thus the following advice is given to analysts of machines: 'Make a rhizome. But you don't know what you can make a rhizome with, you don't know which subterranean stem is effectively going to make a rhizome, or enter a becoming, people your desert. So experiment' (Deleuze and Guattari, 2004, p. 251).

Such experimentation shall lead to other realities since machines also produce 'reality' itself. Thinking the Deleuze and Guattari way means getting rid of questions of how we know the world and turning towards questions of how the world is being constituted in processes, how there is 'world-making' in and through machinic assemblages. The following quote exemplifies this:

> 'An assemblage, in its multiplicity, necessarily acts on semiotic flows, material flows, and social flows simultaneously (independently of any recapitulation that may be made of it in a scientific or theoretical corpus). There is no longer a tripartite division between a field of reality (the world) and a field of representation (the book) and a field of subjectivity (the author)' (Deleuze and Guattari, 2004, pp. 22–23).

Reality turns multiple and is produced through assemblages, which also produce particular observers of reality[17]. The original French word 'agencement', translated into English as assemblage, has a dual meaning of ordering or assembling and of something being an arrangement (Deleuze and Parnet, 1987, pp. vii–viii).

[16] Deleuze and Guattari, similar to Simondon, have a rather positive view of technology and wanted to inquire into possibilities of progressive social change through particular technologies in assemblages, such as Guattari in the following quote: 'You ask how I see future cities, ideal cities? Somewhat like that. Always more creativity, machinic vitality in the domain of technology, sciences, arts, ways of life and of feeling. In saying this, I know that I am rubbing the humanist sensibility of many of our friends the wrong way. It's true. I'm crazy about machines, concrete and abstract, and I have no doubt that a fabulous expansion will eventually break down all the conservatisms that "keep us in place" in this absurd and blind society' (Guattari, 2009, p. 307).

[17] Deleuze and Guattari's theory emphasises the different possible 'worlds' that are made through assemblages. Recently, there has similarly been an 'ontological turn' in STS that turned analyses towards the making of 'worlds' through practices and away from different representations or interpretations of 'one world' (Lemke, 2015; Pickering, 2010, 2014; Marres, 2013; Woolgar and Lezaun, 2013; Law, 2002; Mol, 2002). However, by favouring a process ontology, machinic thinking emphasises the making different of worlds and the possibilities of becoming.

> '[An assemblage] is a multiplicity which is made up of many heterogeneous terms and which establishes liaisons, relations between them, across ages, sexes and reigns – different natures. Thus, the assemblage's only unity is that of co-functioning: it is a symbiosis, a "sympathy". It is never filiations which are important, but alliances, alloys; these are not successions, lines of descent, but contagions, epidemics, the wind' (Deleuze and Parnet, 1987, p. 69).

Deleuze and Guattari locate such co-functionings in wasps that pollinate orchids, in books that are written and read, in metals that react with each other or in big societal formations such as feudalism or socialism – each assemblage changes itself and its elements over time, also in co-functioning with other assemblages. Similar to other concepts such as 'network', 'system' or 'actor-network theory', assemblage offers a way to describe and analyse part-whole relationships. It is a concept with strong ontological claims about how the world is formed in processes of relating heterogeneous elements and the emergent effects of relations.

Deleuze and Guattari's thinking is an effort to come to grips with 'complexity', that there are emergent and non-linear processes, historical transformations, multiple causalities and ontologies, entities with multiple properties and capacities (DeLanda, 2005). Indeed, their writing is strongly influenced by cyberneticians and systems theorists, who, around the same time, were exploring what constitutes 'systems' in relation to their 'environments', how there is 'self-organisation' and non-linear change (e.g. Bateson, Luhmann, Morin, von Foerster)[18]. In these circles the notion of machine was also widely used and much of systems thinking was influenced by the novel 'cybernetic' digital machines. Central for this 'complex thought', as Morin (2008) calls it, is to draw together instead of taking apart, to understand the interplay of different elements and how they relate to each other and create emergent effects.

Recently, the philosopher Manuel DeLanda framed assemblage theory as a theory for social analysis (2006). DeLanda argues that in the dominant organismic metaphor for wholes (e.g. as in 'society as an organism') parts and whole mutually determine each other through 'relations of interiority: [where] the component parts are constituted by the very relations they have to other parts in the whole' (2006, p. 9). Contrary to this, assemblages have 'relations of exteriority' which imply 'that a component part of an assemblage may be detached from it and plugged into a different assemblage in which its interactions are different' (2006, p. 10). Deleuze describes this above with 'co-functioning', 'sympathy' or 'alliance'. Accordingly, assemblage theory shifts the focus of attention to the historically contingent processes that give form to and change groupings and the elements that group together.

To conceptualise these processes of assembling, which can either stabilise or change assemblages, DeLanda (2006, pp. 8–19) uses two axes of analysis. First, there are processes of territorialisation or deterritorialisation, which 'either stabilize the identity of an assemblage, by increasing its degree of internal homogeneity or the degree of sharpness of its boundaries, or destabilize it' (DeLanda, 2006, p. 12). If a wall is built around a city, for example, it territorialises, if the wall gets destroyed, the city deterritorialises. Second, coding and decoding also affects the identity of an assemblage. In social assemblages this is mainly based on discourse and norms, but there can be other forms of coding as well, for example economic coding. DeLanda gives the example that an organisation can be highly coded with strict bureaucratic rules. Another organisation may be based on informal rules and more open to novelty and change and, thus, be rather decoded. An assemblage, as a process, therefore, has spatial, temporal, material and immaterial dimensions that need to be taken into account in the analysis to understand the assemblages assembling in movement, its internal and external flows and connections.

Crucial for DeLanda is that all these processes interact with the capacities and properties of the elements of an assemblage. Therefore, there are no 'essences' of the elements or of assemblages but only concrete

[18] See Pickering (2010) for an insightful study into the motivations and concepts of early cybernetics.

and manifest, historically produced capacities and characteristics. Ingold (2011, 2013), drawing on Deleuze and Guattari, similarly argues that all entities in a world that is alive, e.g. materials, organisms or artefacts, move along a line, a trajectory with a history, present and possible futures. During this they entwine and correspond with elements in movement, which changes their paths. Through being in an assemblage, elements acquire certain properties, but these need not necessarily encompass all their capacities. In a different assemblage, other capacities of an element may be activated. Therefore, each assemblage creates 'spaces of possibility' which enable and constrain what the assemblage as a whole or certain elements can 'do' (DeLanda, 2011). Each element, however, is not a distinct entity, but it is itself an assemblage. An assemblage is formed of assemblages, none of which is reducible to another, and each of which is itself a process. Yet assemblages form recognisable entities and can be rather stable, and it is an empirical demand to analyse the processes of stability or of transformation (Harman, 2013).

Although Deleuze and Guattari's thought is meant to see everything as a machinic assemblage, their work also entails a philosophy of technology on which I concentrate now, since this provides further links to a thinking of TechKnowledgies. Indeed, in many of the social assemblages they explore, technologies play an important role; the book in the assemblages of literature, the stirrup in the feudal war assemblages of horse fighters or the TV in consumer assemblages. It is, however, the special way in which technical objects are being conceived as parts of machinic assemblages that is central to thinking of TechKnowledgies and assemblages together:

> 'But the principle behind all technology is to demonstrate that a technical element remains abstract, entirely undetermined, as long as one does not relate it to an assemblage it presupposes. It is the machine that is primary in relation to the technical element: not the technical machine, itself a collection of elements, but the social or collective machine, the machinic assemblage that determines what is a technical element at a given moment, what is its usage, extension, comprehension, etc. [...] Thus one cannot speak of weapons or tools before defining the constituent assemblages they presuppose and enter into' (Deleuze and Guattari, 2004, p. 439, italics in original).

This statement entails a fundamental difference in machinic thinking of technology to other forms of thinking in 'sociotechnical' and 'symmetrical' (ANT) ways about technology and society. Typically, when sociologists or STS scholars think sociotechnically, it is 'technical object + something social' – both are important and do somehow interact. Deleuze and Guattari go further. They not only say that technical objects are part of assemblages. They also say that the machinic assemblages – of course made of heterogeneous parts – are 'primary' in relation to technical objects. It is the machinic assemblage that enables, changes and unfolds the technical object. This also means that particular machinic assemblages enable particular technical objects and not others; the arrangement of the whole assemblage includes and excludes certain technical objects. Theirs is thus a political philosophy of technology that is interested in how particular organisations of social life entwine with particular technical objects. The inquiry of technical objects immediately leads beyond the object and, as Guattari puts it, to see

> 'the necessity of expanding the limits of the machine, stricto sensu, to the functional ensemble which associates it with man. We will see that this implies taking into account multiple components: material and energy components; semiotic, diagrammatic and algorithmic components (plans, formulae, equations and calculations which lead to the fabrication of the machine); components of organs, influx and humours of the human body; individual and collective mental representations and information; investments of desiring machines producing a subjectivity adjacent to these components; abstract machines installing themselves transversally to the machinic levels previously considered (material, cognitive, affective and social)' (Guattari, 1995, pp. 34–35).

Put another way, machinic thinking of technology asks how particular technical objects are connected to the social machines in which they are conceived, designed, produced, used, destroyed and so on. Much needs to be in place for a particular technical object to exist and to be taken up in a particular social arrangement. Deleuze and Guattari pursue a non-linear thinking of technology. They show how marginal technical objects in one place and time can have a significant impact somewhere else; there is no simple mechanism that takes an object from its invention to its diffusion in society: 'the industrial "take off" of steam engines happened centuries after the Chinese Empire had used them as children's toys' (Guattari, 1995, p. 40). Deleuze and Guattari do not equate 'technical machines' and 'social machines'. Somewhat similar to von Foerster's differentiation between trivial machines (clearly determined) and non-trivial machines (inherently uncertain and non-linear) they locate socio-historical complexity in social machines (cf. Hörl, 2012). All technical machines, however, must not be conceived without their outsides, the collective machines within which they work. Since each technical object or machine is always dependent on an 'outside', there is complexity in technology, in the complex relations that technical objects depend upon. In machinic thinking conceiving of linear and determined technology – as common in much criticism of technology – does not work, since there is no technology without a complex collective machine and, therefore, no linearity.

In the quote above Guattari refers to a central aspect in machinic thinking, namely 'abstract machines' that are installed across the different heterogeneous elements of a collective machine. Abstract machine is central to *A thousand plateaus* (Deleuze and Guattari, 2004) and it is indeed a further and important aspect that differentiates machinic thinking from other concepts for conglomerations such as ANT. As Pasquinelli (2015) shows, Deleuze and Guattari were inspired by cybernetics and its concept of algorithm as an abstract machine. In cybernetics an abstract machine designates a procedure that can be realised in different ways, different concrete machines, for example in a software program or manually with the help of a sheet of paper. Abstract machines for Deleuze and Guattari, however, are not confined to computational logic – neither is the concept of algorithm confined to computation – but designate procedures that produce movements and flows through connecting different elements in a process[19].

The abstract machine is that which arranges heterogeneous elements into a productive entity, a machinic assemblage or collective machine (Livesey, 2010). Also different to most software algorithms, abstract machines, through being realised, are not necessarily determined procedures that create the same effects over and over again. Instead, abstract machines create productions of surplus in the collective machines through which they are realised (Pasquinelli, 2015). Abstract machines amplify and change flows, they organise productive forces, they change reality through organising a particular process through a procedure. Abstract machines are not independent from collective machines, but they transcend individual concrete manifestations of a collective machine. An abstract machine is typically realised in many different collective machines that can have different elements, which are nonetheless organised similarly (DeLanda, 2006). While abstract machine and collective machine are not the same, they are dependent on each other: 'The abstract machine is like the cause of the concrete assemblages that execute its relations; and these relations take place "not above" but within the very tissue of the assemblages they produce' (Deleuze, 2006a, p. 32). While Deleuze speaks of one abstract machine as the cause of many machinic assemblages, Guattari wrote about plural abstract machines that install themselves in one collective machine. Indeed, considered from the machinic ontology of heterogeneous connections both is possible; novel machines might form precisely because different procedures enable a connection of elements. This, however, is an empirical question.

[19] As Serres (2015) and Harari (2016) both emphasise, however, algorithmic knowledge is nowadays becoming a dominant form of knowledge because digital algorithms are becoming pervasive in all spheres of social life where they entwine with other procedures through which society organises itself.

Let me illustrate this with the example of cooking. A cooking recipe is an algorithm, a procedure to produce a meal, an abstract machine. In a cook book one only finds the representation of this procedure, but it is realised in the process of cooking, which is a process of forming a collective machine of a subject, ingredients, technical objects and energy. The same recipe can be, and often is, realised in multiple forms, different collective machines that produce different concrete meals. Before the process of cooking, however, people and technical objects have to be produced and organised to be enabled to produce a meal together. There are collective procedures that shape how people learn to cook and what kinds of objects are available for a particular way of cooking. Such abstract machines of cooking in agricultural societies differ from those of industrial societies and there is even a special abstract machine for the production of professional cooks and corresponding restaurant meals.

Following on from the above, *I define a TechKnowledgy as an abstract machine that produces and organises technology and knowledge through producing corresponding collective machines. In other words, a TechKnowledgy is the 'logic' that assembles heterogeneous elements into machinic assemblages. It is a historically emergent and dynamic set of collective procedures that produce and organise technology and knowledge.* TechKnowledgies, however, are not invented on a sheet of paper but develop through the connections of historically changing procedures. Again, we can draw inspirations from recent studies on algorithms. Pasquinelli writes that 'algorithms are never autonomous objects in themselves and like Marx's machines they are continuously redesigned and reinvented by the pressure and changes of external forces' (Pasquinelli, 2015, p. 62). Some digital algorithms, as used in finance, for example, adapt and change in relation to their environments. They have been designed in such ways that their continuing change becomes relatively autonomous from the initial designers but dependent upon dynamic environmental relations, e.g. the results of other algorithms that reconfigure them (Schmidt, 2016). Through analysing and observing different collective machines, the analyst can create an 'abstraction' to document the contours of the shared abstract machine. The abstraction of the abstract machine of open digital fabrication into an ideal-typical procedure is documented in the concluding chapter of this study.

The following figure shows the relationship in another medium. Each collective machine is a singular entity in a process but the same – at least similar – procedures can take place within different collective machines. These do not determine the fate of the elements within them, but shape spaces of possibility that have an impact on the elements' becoming; machines interrupt flows and create connections between different elements. Changes in collective machines that are repeated in others can lead to changes in the abstract machine that typically structures the procedures. Machinic thinking also demands the thinking of machines within machines. That is, one should also think of 'zooming out' and see a larger collective machine emerge with several smaller collective machines as parts. For example, one FabLab can be considered a collective machine within the global collective machine of FabLabs. In the latter one, not everything is connected, yet the labs together shape a shared space of possibility and share a TechKnowledgy. In the figure, TechKnowledgy A can be found in three collective machines. Although the collective machine that entails three 'smaller' collective machines as parts also entails TechKnowledgy B, TechKnowledgy A has overall the main influence on the interruptions of flows.

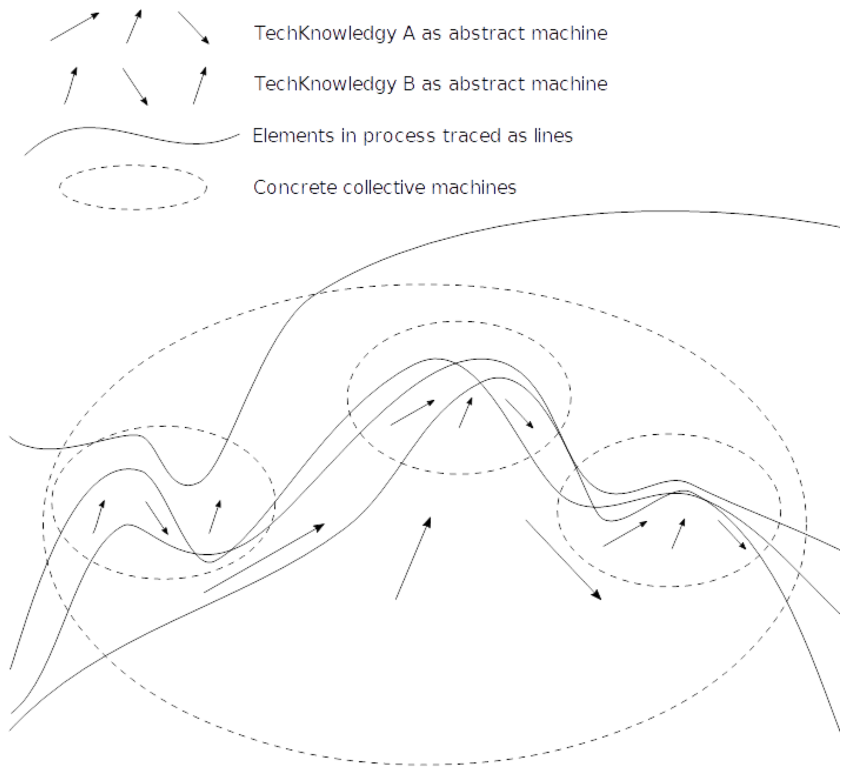

Figure 2.1: Schematic of TechKnowledgies

In the following I delve deeper into machinic thinking by locating it within other corpora of thought that have influenced it and share a focus on similar complex problems of 'assembling'. I start with Karl Marx's thinking of industrial machines, then I discuss Lewis Mumford's analysis of the megamachine and relate Deleuze and Guattari's machinic assemblages to Foucault's apparatuses. Each of these discussions helps to develop an analytical vocabulary to grasp the heterogeneous collective machines in a TechKnowledgy. From Marx I take the importance of organisational forms, from Mumford the role of desires and from Foucault the production of subjects that together with Simondon's technical objects form the elements that my inquiry into the TechKnowledgy of open digital fabrication focuses on. I end this theoretical discussion by comparing the machinic thinking reached at that point with ANT, from which an inquiry into TechKnowledgies can learn the attentiveness to heterogeneous relations and empirical details.

2.3.1 Marx's fragment on machines: organisational forms

In 1858, Marx wrote a few pages on industrial machinery and knowledge that would only from the 1960s onwards be rediscovered as a foundational text for many authors who write about 'cognitive', 'immaterial' or 'knowledge' capitalism (e.g. Gorz, 2010a). The so-called 'fragment on machines', however, is also a good way to go further in machinic thinking and TechKnowledgies, especially as it considers the problematic of technology and knowledge in early industrial capitalism.

In the text, Marx explores the relations of fixed capital (machinery, factory building etc.) to waged labour and how they together form the workings of the capitalist factories of his day. Already about one hundred years before Deleuze and Guattari, Marx is quite good in machinic thinking. He points out how the relatively new large machinery fundamentally changed work. Formerly, the labourer with a tool was the source of the production process in manufacture where manual work produced commodities. With the advent of machinery the labourer merely serves the workings of the machine, which is an 'automaton consisting of numerous mechanical and intellectual organs, so that the workers themselves are cast merely as its conscious linkages' (Marx, 1858 n.p.). Workers have become only parts of a larger machine, that determines their rhythms and levels of autonomy in work. Furthermore, Marx argues, while the workers are part of the functioning of machinery, they do not know about the internal organisation of the technical machine since they only work on clearly defined tasks – this is similar to Simondon's critique of the splits of the technical process. This is the foundation of the Marxist critique of 'deskilling' through technology, which argues that the power and cost of labour is reduced through complicated machinery that reduces human work to a dire routine and which became rejuvenated in the advent of digital automation (Braverman, 1974).

In machinic thinking we have to consider the fragment on machines within Marx's wider analysis of human history and capitalism. Central to Marx's analysis is the idea that humans produce themselves and their society through work, i.e. the combination of economic relations and technology – which does not mean that all work is paid labour as is dominant in capitalism. Human life is, therefore, historical and transformative and through other kinds of work other kinds of humans are possible. In his analysis of capitalism Marx then points out that the working class is dependent upon selling their labour power, i.e. parts of their life time, to capitalists, who own the means of production (amongst them technical objects) and buy the commodity of labour to use it in their projects and to make profit in selling the products of labour. Back to machinic thinking, the machineries of industrial factories, therefore, depend upon the machines of labour markets and machines of finance ('circulating capital'), both of which can also destroy individual companies. Deskilling, then, is not only an effect of a particular 'technical' necessity but of power constellations between social classes that are being produced by these machinic assemblages. Noble showed how there were many options to design digital machinery after the Second World War, yet, many managers and engineers opted for the designs that would deskill labour and weaken its power and were, therefore, thought to be more profitable (Noble, 1984).

Key to Marx's analysis of the collective machines of industry are organisational forms. The organisational form of a labour market is central to enable the formation of factories where these markets entwine with hierarchy as organisational form within the company, e.g. between workers and engineers and owners, stabilised through technical objects. And these labour markets are embedded within markets for commodities that are the organisational form for the interaction and competition of companies. From such a Marxist perspective we can also learn that organisational forms are not simply invented on the spot when a new organisation is born. Labour markets, for example, took decades to develop and to become a dominant organisational form during the industrial revolution (Polanyi, 1978). Any analysis of organisational forms, also as part of an analysis of a TechKnowledgy, however, needs to be careful and empirically sensitive to the particular constitutions of collective machines[20]. One can, however, get further inspiration from Marx for these novel machines and their relation to knowledge.

Considering knowledge, Marx remains ambivalent and even heralds an emancipatory potential of machinery. Machinery, he argues, is not simply owned by capitalists, but is made up by the products of labour of others; it is an assembly of technical and scientific knowledge, an expression of the collective knowledge of societies. Machinery and technology in general is 'the power of knowledge, objectified. The develop-

[20] Notably, one of the by now classic theories for open-source projects argued that they are based on a novel organisational form, that of 'commons-based peer-production'. This was seen as performed by self-organised volunteers and it was presumed to be different to markets and hierarchies (Benkler, 2006). By now such separations between these organisational forms do not work anymore for most open-source projects, since hierarchies and markets have been shown to often be involved in these (Schrape, 2016; Tkacz, 2015). The popularity of the concept commons-based peer-production, however, shows the significance of novel organisational forms that emerged 'online' and the need to find notions for them.

ment of fixed capital indicates to what degree general social knowledge has become a direct force of production and to what degree, hence, the conditions of the process of social life itself have come under the control of the general intellect and been transformed in accordance with it' (Marx, 1858, n.p.) As Gorz (2010a) notes, however, Marx is terribly imprecise in his usage of what he means with 'knowledge' in this passage. Is it explicit knowledge inscribed into the technical objects? Is it (techno)scientific knowledge production? Is it the social knowledge of how to organise social life? Despite this imprecision there is an interesting difference that Marx introduces throughout the pages of the fragment. On the one hand, he talks of machinery as fixed capital and as private property, and on the other hand, machinery is the objectification of general, collective knowledge. The problem that Marx, somewhat implicitly, describes here, is how knowledge – collectively produced – is being turned into private property. This problem and its increasingly difficult 'solution' sits at the heart of many debates on 'knowledge capitalism' and possible alternatives to it through common knowledge enabled by the Internet (Mason, 2015; Hardt and Negri, 2009).

Marx, therefore, argues for an ambivalent account of technology. On the one hand, it alienates and deskills workers. On the other, he sees dramatic potential in the technologies of his day to produce the necessary goods for social life and to decrease the labour time of humans. If, Marx speculates, machines produced most of the stuff for consumption, then people have much more time to pursue freely chosen activities and they can advance their individual knowledge and, therefore, also social knowledge. More and better collective knowledge would then lead to even better technologies which would lead to even less working time. He explicitly states that technology could become an emancipatory force in human history. This is part of utopian socialist thinking that emerged in the 19th century. Such thinking, however, is currently being rejuvenated in interesting ways in light of the contemporary wave of the digitisation of knowledge and even stronger automation. Again, this debate entails the hope and the demand for less working hours and more time available for people to contribute to common knowledge (Mason, 2015; Srnicek and Williams, 2015). Although Marx's hopes were disappointed, this gives a further hint for Marx-inspired machinic thinking. Besides the machinic assemblages of the factory, it is important to take the collective machines into account that produce and circulate knowledge. How do they produce knowledge that ends up objectified as machinery inside a private factory? How are there particular TechKnowledgies entwined with particular economic settings? And, by taking some of the utopian tradition on board, how can such machines work without tight control of knowledge through private property?

Marx's early ventures into machinic thinking provide a politico-economic take on machines. The politico-economic awareness – that Deleuze and Guattari had – highlights the entanglement of capital and technical artefacts with the asymmetric formation of bodies and collectivities, in Marx's writing the workers and the capitalists. The abstract machine of capital, that is the search for profit, produces collective machines that serve it. Furthermore, different 'logics' have an impact on machines. The logic of private capital controls workers and artefacts for profit, yet, the workers and artefacts also participate in 'general social knowledge' which transcends individual firms and is related to other collective machines. There is an inflow and outflow from collective machines that can include money, artefacts, people and knowledge. Marx hints at the paradoxes and ambivalences in the juxtaposition of private and collective logics. One has to think beyond particular collective machines such as a firm and connect them to larger productive processes in their environment, in the examples discussed capitalist economic structures and collective knowledge production. The interruptions and productions of flows that these produce are not simply smoothly in line with the workings of particular machines. Machines are multiple and paradox, and this entails their politico-economic aspects as well.

2.3.2 Mumford's myth of the machine: desires

Another central influence for Deleuze and Guattari was the work of Lewis Mumford. Although Mumford was a highly influential intellectual of technology, who also inspired David Noble, Thomas Hughes and

Langdon Winner, his work has been largely forgotten in STS (Hughes and Hughes, 1990). Mostly known for his critique of the 'megamachine', a term adopted by Deleuze and Guattari, Mumford's thinking of modern technology is rich and multifaceted. Writing his first book on technology, *Technics and civilization* in the 1930s Mumford was at pains to argue that technology is within human culture and also shaped by it in 'rational' and 'irrational' ways. In this text, one finds another version of stating that the collective machine is primary to the technical machine.

> '[T]he fact is that in Western Europe the machine had been developing steadily for at least seven centuries before the dramatic changes that accompanied the "industrial revolution" took place. Men had become mechanical before they perfected complicated machines to express their new bent and interest; and the will-to-order had appeared once more in the monastery and the army and the counting-house before it finally manifested itself in the factory. Behind all the great material inventions of the last century and a half was not merely a long internal development of technics: there was also a change of mind. Before the new industrial process could take hold on a great scale, a reorientation of wishes, habits, ideas, goals was necessary.' (Mumford, 2010, p. 3)

The analysis that follows this grand statement is an excellent example of an assemblage analysis since Mumford traces changes in ideas and material environments and shows how they are related. He shows how an ancient world, incapable of conceiving and supporting modern machines, was re-made to become the foundation of modern technology. Mumford is, therefore, also a writer on ontology, interested in the worlds that enable and sustain industrial technology. He shows how modern standardised time was invented and practised in monasteries[21], how transport through ships and canals standardised movement, how the emerging capitalist economy conceived of things in abstract quantities and how science from the renaissance onwards wanted to harness the 'objective laws' of nature and how they together 'formed a complex social and ideological network, capable of supporting the vast weight of the machine and extending its operations still further' (Mumford, 2010, p. 59). 'The machine' in Mumford's writing is not an artefact such as a steam engine but an interdependent complex within which such artefacts become central and admired objects. And although Mumford, inspired by radio and television, hoped that a new phase of technology would enable a 'more organic' form of life, the next thirty years lessened his hopes.

In his more popular book *The myth of the machine*, written in the 1960s, Mumford's theory became even more political as he argued for the destructive effects of 'the megamachine', which he thought to be the central feature of the bureaucratic and authoritarian post-war societies he condemned. Mumford traces a first megamachine in human history back to Egypt thousands of years ago, where in his thinking the slaves building pyramids, the military overseeing them and the Pharaoh as a quasi-god towards whom the effort was directed formed a machine – and no artificial engine was necessary for it. The second megamachine instead is based on the exploitation of energy through technical machines and it forms a 'pentagon of power': power in the form of energy and political power of centralisations. Its 'pyramids' are the space rockets, atomic bombs and skyscrapers. The 'slaves' pursue standardised tasks in mechanised and hierarchical firms and consume the standardised products of industry in their standardised suburban homes. And the 'god' that the megamachine is built around is the combination of technical progress and economic growth for technical progress's and growth's sake. The megamachine has become a self-perpetuating system that seems as if it was out of control. Indeed, Mumford is extremely critical of this megamachine. However, he also argues for an alternative that would be built around the 'creativity of life' and produce and use technology in the service of this.

[21] In some respects, Mumford's study is similar to Foucault's history of disciplinary power (Foucault, 1995). Both focus on particular practices of shaping and training self and body based on modes of standardised knowing.

What we explicitly find in Mumford's later thought is a political theory of technology that links particular technological structures to forms of life and social organisation[22]. In another text, Mumford wrote about 'authoritarian and democratic technics' (Mumford, 1964). The first denotes the megamachine and the latter denotes decentralised and multiple machines, open to change and creativity and autonomy of the people who are part of them. This would entail

> 'the reconstitution of both our science and our technics in such a fashion as to insert the rejected parts of the human personality at every stage in the process. This means gladly sacrificing mere quantity in order to restore qualitative choice, shifting the seat of authority from the mechanical collective to the human personality and the autonomous group' (Mumford, 1964, p. 8).

Mumford's idea is that 'democratic technics' would not simply rely on 'more democratic' processes of decision-making within the megamachine but instead be constituted by a machine with other qualities, in which flows are differently produced and differently interrupted[23]. It would in Mumford's thinking also be a machine that treats humans not as rather clearly defined parts of machines but as elements with more autonomy and the ability to influence the machine, basically as capable of choice. While Mumford relies on a dualist mode of thinking, either the megamachine or something else, in Deleuze and Guattari there is a thinking of multiple machines and multiple 'worlds', and in such a rhizomatic world no machine is total, new connections can at least be tried anywhere. But they share Mumford's political ideas that the reconstitution and creation of novel collective machines is the political task at hand. Machines in which technical artefacts are being connected to play different roles and unfold differently, in which there are productions of different theories, different subjects and organisations. A key message is that machines can have different characters or styles and this also in terms of their internal politics.

There is one more central output of Mumford's writing that resonates well with Deleuze and Guattari and with the purposes of machinic thinking here. Part of the 'power complex', as he also calls the megamachine, are imaginary and libidinal aspects of human life. Utopias, fears, hopes, dreams and imaginations are part of the megamachine and indeed all of technology throughout human history in Mumford's view. Mumford sees the root of technology not in the necessities to adapt the body better to hostile environments but in the creative and symbolic powers of the human mind. Every technical arrangement in human history is entwined with symbolic and imaginative textures; for the megamachine it is the 'myth of the machine'. The following digression into contemporary analyses of technoscience reveals the strength of Mumford's ideas.

[22] In his classic text 'Do artifacts have politics?' Winner (1980) does not only muse on Moses's racist bridges, too low for public transport and, therefore, restricting access of poor and mainly black groups – the much cited example – but considers nuclear power plants as well. The latter, at least in the form as they were built, he argues inspired by Mumford, are enabled and dependent upon authoritarian and bureaucratic structures.

[23] Mumford is not simply the cultural critic and pessimist that he is often portrayed as – he actually believed in the possibility of other forms of technology and human life and speculated about them. He thought that another technology would be based on other theories of life, other habits of the body and social organisation that would foster creativity and that there were already visible signs of such a possible shift (Hughes and Hughes, 1990). These ideas are somewhat similar to Illich's conception of 'convivial tools' that he wrote about also in the 1970s. He argued that the 'crisis [of industrial society] can be solved only if we learn to invert the present deep structure of tools; if we give people tools that guarantee their right to work with high, independent efficiency, thus simultaneously eliminating the need for either slaves or masters and enhancing each person's range of freedom' (Illich, 1973, p. 23). Illich's 'conviviality', with which he designates 'the opposite of industrial productivity [...] autonomous and creative intercourse among persons, and the intercourse of persons with their environment', is currently being rediscovered and argued for anew in the 'convivialist manifesto', written by dozens of well-known intellectuals and addressing many spheres of society besides technology (http://www.lesconvivialistes.org/abridged-version-of-the-convivialist-manifesto, accessed April 2016). A recent argument for a new style of collective machines is made by Jeremy Rifkin who argues dualistically that digitally enabled 'lateral power' is replacing the vertical and hierarchical organisation of industrial modernity (Rifkin, 2014).

Technoscientific transformations of myths

Drawing on Mumford in this respect, Nordmann (2016) argues that in recent history, imagined technologies, e.g. futuristic visions of nanotechnology or synthetic biology, have become novel 'myths' which precede any material technologies. By conceiving their futures in terms of technoscientific futures, Nordmann continues, societies have formed social machineries that replace politics with conceptions of co-design and, therefore, risk becoming apolitical. The belief in 'magical' technologies as the saviour of human history is in Nordmann's argument an ideology of societies that neither understand themselves nor their technology and, therefore, resort to imagined futures of technologies. Nordmann argues that at least in imagined terms and in experimental settings the industrial megamachine is replaced by the myth of 'soft machines'. In such soft machines, technologies and socialities are imagined as malleable and mutually informing each other. Soft machines posit an imperative to co-design new technologies, of which Nordmann, however, is sceptical: 'Mumford, in particular, elaborated the historical significance of a technology that initially existed only in the imagination. This is what we are seeing also today: the soft governance model of a collective social experiment with new technologies suggests the emergence of a social order in which producers and developers voluntarily agree to be accountable, in which consumers willingly act as guinea pigs, in which analytic expertise is spread among all participating citizens, in which monitoring by state agencies is replaced by permanent vigilance distributed over an indefinite number of actors' (Nordmann, 2016, p. 212).

In reaction to new and emerging technologies and the growing influence of technoscience and technoscientific claims about shaping the future, many scholars have turned towards the role of 'futures', 'imaginaries' or 'visions' in the governance of innovation processes (Jasanoff and Kim, 2015; Kaiser, 2015; Grunwald, 2014; Rip, 2012; Dickel, 2011). In the past years much research has shown the importance of imaginations of the future in innovation processes. It has been shown how innovation actors mobilise and are mobilised by particular expectations of what the future is supposed to bring (Borup et al., 2006). Visions have been shown to be important media for communication processes between different actors and, therefore, they are means of governance (Lösch, 2010, 2014). Shaping, using, communicating, believing and contesting imaginations of the future is a strategic activity in technoscience and innovation processes, so-called 'visioneering' (McCray, 2012). The historian Patrick McCray (2012) has shown how during the past decades certain technoscientists, such as Eric Drexler for nanotechnology, successfully created, mobilised and promoted imaginations of the future to push particular technologies and agendas. These 'visioneers', as McCray calls them, did not only think of a future, but created coalitions and networks (e.g. to politicians, business leaders, publics), organisations and technologies which together 'could mobilize, explore, and push the limits of the possible' (McCray, 2012, p. 10). The focus of the analysis is on the processes that mobilise visions in the present and how visions are strategically used to influence and transform the present. Visioneering is thus productive of imaginations, social and technical realities in the present – and these need not be the realities that were imagined at first (Lösch, Heil, Schneider 2017; Sand and Schneider 2017). Taken together, these insights show that the shaping, usage and circulation of imagined futures has become a technosocial skill for acting technologically (Rip, 2012) in an unfolding 'age of technoscience' (Nordmann, 2011).

From such research we know that struggles about the definition of the future are part of contested innovation processes and of the reconfigurations of the technologising society we live in. Research, however, has also shown that although actors sometimes claim to know the future or are certain about drivers towards particular outcomes, such claims, forecasts or predictions have their effects in shaping the present. Imaginations of the future are always produced and effective within the present. While this debate has contributed important insights into the social studies of innovation and the politics of innovation, most of the research named above focused on discourse and imaginations as narrated texts. In light of a machinic conception of the world, this is not enough. There are, however, recent studies that move *from a discourse-centred approach to analysing imaginations of the future in relation to arrangements of social practices and to anticipatory practices (Alvial Palavicino, 2016; Lösch and Schneider, 2016; Nordmann, 2016).*

If we build upon Nordmann's argument of a contemporary reconfiguration and exploration of collective machines beyond the standardised control of the megamachine, we can also see how the idea of 'openness' is part of such reconfigurations. Openness is one of the key ideas and ideals that circulates in the networked cultures of hacking and open-source technologies and is often used as a normative vision. Already in the early days of free software and open-source software, the definition, design and contention of 'open' arrangements was an integral part of the hacker culture, a technoscientific culture that began to form (Coleman, 2012; Kelty, 2008; Himanen, 2001). By now, however, with 'openness' being used as a label in open-source hardware projects, Wikipedia, open government, open data, open science and others, this term has gained a much wider and fuzzier meaning and has become attractive beyond the hacker sphere. Indeed, it cannot be confined any more to countercultural movements. Diverse actors from different spheres have visioneered openness into a desired future. For example, a particular form of openness has become an important moral value in the emerging technoscience of synthetic biology, where open-source competitions are being held (Bensaude-Vincent, 2016).

In the most wide-ranging study on the 'politics of openness' to date, Tkacz writes that 'openness must therefore be understood as a powerful new form of political desire in network cultures' (2015, p. 28) and this includes business, politics and grassroots movements. Openness cannot be reduced to one particular aspect since it is found in very different practical settings, which all enact their particular form of openness. Together with its relation to digital networks the discourse of openness is filled with calls for participation, transparency and sharing through digital technology, it alludes to collective agency and ideas of publicness. According to Tkacz, it is therefore necessary to investigate the different and particular ways in which openness is being organised (Tkacz, 2015). However, openness is not simply a discursive phenomenon, but rather is a practical engagement in the world. Openness is guiding and being contested in discursive and practical evaluations through engagement (cf. Thévenot, 2002). A whole 'ethos of openness' has emerged that takes part in deciding and legitimating what is 'good' and 'bad' about the practices and the distributions of their effects amongst the people involved. Such an ethos, however, is differently put into practice in 'moral economies'. Investigating these means to turn towards 'the moral justifications of basic features of economic organisation [and] the moral influences on, and implications, of economic activities, and how economic practices and relations are evaluated as fair, unfair, good or bad by those involved in them' (Sayer, 2015b, p. 2). How this takes place is analysed in respect to the Lasersaur and FabLabs in later chapters.

We might say that the growing number and importance of imaginations of the future in light of technoscientific products and logics signifies the demise of industrial myths of technology. Imaginatively the spectrum of myths has widened and in turn novel configurations of technology are imagined. The future has become malleable and is contested and differently envisioned and desired. Yet, practical settings or even institutionalised arrangements that stabilise experimental co-designs of novel technologies and socialities are still lacking.

The theory of machinic assemblages is a fruitful way to entwine imaginations of the future with social arrangements of which they are the effect or the cause or both. Such an entwinement differs from most other approaches to studying technological visions and imaginations that focus mainly on discourse and semantics. Following Deleuze, Guattari and Mumford, it is imperative to do so for an understanding of TechKnowledgies as pursued here. Imaginations of the future and practices are not separated. With machinic thinking we can move beyond the mainstream approach in the social sciences which investigates how futures are thought of and communicated in the present and are construed as simply part and effect of discourse. Such an approach takes time out of the future and neglects its reality, open and unknown as it might be (Kaiser, 2012; Adam and Groves, 2007; Bloch, 1995). Many imaginations of the future that are effective in innovation processes engender desires by being enacted as futures that actors wish to attain. For such desired futures or visions machinic thinking offers an ontology which is fruitful for the needs of the analysis of TechKnowledgies:

> 'Assemblages are passional, they are compositions of desire. Desire has nothing to do with a natural or spontaneous determination; there is no desire but assembling, assembled, desire. The rationality, the efficiency, of an assemblage does not exist without the passions the assemblage brings into play, without the desires that constitute it as much as it constitutes them' (Deleuze and Guattari, 2004, p. 399).

There is no machine without configurations of desire and no desire without configurations of a machine – McCray's analysis of visioneering also pointed this out. From this perspective, imaginations and how they engender desire is not simply a form of interpreting collective machines but is in fact functionally necessary for collective machines to operate. Yet desire plays a double role in Deleuze and Guattari's work. On the one hand, there is the ontological claim that it is always beyond individual 'minds', constituted within the heterogeneous relations of machines. Desire therefore is not only co-produced by people but it also co-produces them. On the other hand, however, desire is assigned a political role. Deleuze and Guattari argue that there have to be 'desiring machines' that strive for novelty and social change; machines that produce differently through trying other connections and interruptions of flows; '[d]esiring machines which break with the great interpersonal and social organic equilibria, which invert orders' (Guattari, 1995, p. 52). To desire differently means to connect machines differently. What is important here is that desire is conceived as a link between what is and what is not-yet; it sits on the verge of an unfolding present, it is part of the becoming of collective machines.

What are the main take-aways from this discussion of Lewis Mumford's work in relation to machinic thinking? First, a widened understanding of the idea of a primacy of the collective machine in relation to technical artefacts. The historical ontology, the made 'world' is the substrate that enables particular versions of collective machines that enable particular artefacts. This ontology includes conceptions of time and space, social order and legitimate power, the formation of bodies and minds, theories and ideas of technology and economy and more. Second, such 'myths' of the world are being put into practice through the creation of machines in which people function as parts, and this includes practical and symbolic tasks that they fulfil. Third, machines in society are thoroughly political; they produce particular effects and exclude others. Machines can have particular political styles that correspond with their forms; empirically there might be hierarchical machines, anarchic machines, large and small machines, democratic machines, convivial machines and so on. Fourth, every machine is organised by and organises desires; it produces and unfolds wishes, and these can entail imaginations of desirable futures which make people try to change the machines of which they are part.

2.3.3 Foucault's apparatuses: subjects

Much more well-known in sociology than Deleuze and Guattari's work is the work of Michel Foucault. And within Foucault's later studies the concept of 'apparatus' (or 'dispositif') is somewhat similar to collective machines (Foucault, 1980, 1998). Indeed, not only is 'apparatus' also a technical metaphor for social analysis, but Deleuze (2006b) even discusses Foucault's notion in close relation to his thinking in assemblages[24]. Rabinow and Rose point out a feature of the concept of apparatus that I think is transferable to machinic assemblages.

> 'Social theory had tended to work in terms of institutions, classes, and cultures and, in a distinct register, in terms of ideas, ideologies, beliefs and prejudices. But in introducing the concept of apparatus, Foucault cut reality in a different way. In cutting across these categories, new and rather different elements, associations and relations can be seen' (Rabinow and Rose, 2003, p. xv).

Indeed, I think that apparatus and machinic assemblage cut reality in a rather similar way, although they focus on different products of such cuts. Foucault's apparatus resides within his main project to analyse how 'subjects' have been formed through power/knowledge constellations. In an interview, Foucault clarifies what he understands as an apparatus (Foucault, 1980). An apparatus consists of a network of heterogeneous elements (discursive and non-discursive, ideas, materials, etc.). The relations that are being established amongst these elements have a particular 'nature' that guides the ways of their variation and transformation. And together the apparatus is of a strategic nature, it emerges historically in reaction to a particular crisis to which the apparatus offers its constructed solution. Typically, Foucault's apparatuses would be seen as vast and epochal formations, e.g. disciplinary power, modern sexuality, and they would be seen as governing whole populations and subjects (cf. Lösch and Schneider, 2016).

In *Discipline and punish* Foucault (1995) does not yet speak of apparatuses, but the study can be seen as an analysis of an apparatus. Then, for example, disciplined subjects have been formed through the apparatus of disciplinary power, which entails prisons, schools and factories amongst other institutions. Within these, people are being measured against and formed through particular constructed knowledges of 'normality', which range from how to sit correctly at a desk in school to how to behave according to the rules of the prison or how to follow a particular time regime in industrial production. Disciplined subjects are, therefore, produced through particular ways of knowing and assessing, which include material settings like architecture, and these ways of knowing are at the same time ways of enacting power since they shape and transform people. Power, according to Foucault, is relational, it is not held by individual actors (i.e. 'the powerful'), but it resides and moves within relations. Through the 'panopticon', an observatory in a prison from which the prisoners can be seen all the time but the prisoners cannot see the observer, Foucault very concretely describes such relational power. Since the prisoners cannot be sure whether they are observed or not, they internalise the eyes of the observer and behave how she would demand it, whether or not she is in the panopticon. Power is in this example enacted in the relations between observer and observed, forming both and constructing particular norms and knowledges which in turn construct power.

What are similarities and differences of apparatus and collective machines? Similarly, both concepts draw attention towards historically emergent complexes of heterogeneous elements, their relations and how they produce and transform entities. However, Foucault's work is focused on the production of subjects, whereas Deleuze and Guattari are interested in heterogeneous productions, of people, things, organisms, institutions,

[24] 'Apparatuses are therefore composed of lines of visibility, utterance, lines of force, lines of subjectivation, lines of cracking, breaking and ruptures that all intertwine and mix together and where some augment the others or elicit others through variations and even mutations of the assemblage' (Deleuze, 2006b, p. 342). See also comparisons of Deleuze and Foucault (Altamirano, 2014; Legg, 2011).

organisations, emotions and so on. Related to this is that Foucault has mainly worked on and is mainly read as focused on discourse. In Foucault's later work, there are hints that he also thought of a 'government of things' including materials, territories, diseases and so on (Lemke, 2015). Deleuze and Guattari, however, explicitly address the question of heterogeneous becoming and of an ontology of social life, including humans and things, and provide a more detailed vocabulary for it, paired with concrete analyses. Furthermore, whereas Foucault sees apparatuses as decades- or even centuries-old constellations, the artificiality and social construction of which is highlighted by him, Deleuze and Guattari see machines across different registers of time and stability. There might be centuries-old machines, yet, Deleuze and Guattari also point out the spontaneous groupings, the small connections and transformations, the flux and becoming of multiple machines, their creative instability[25].

Deleuze muses on how there have been two faces of Foucault across his work. In his books, Deleuze argues, Foucault was the analyst of the history and power of apparatuses, whereas in his interviews, which complement the books, he turned towards diagnoses of the present and possible becomings. 'History is the archive, the design of what we are and cease being while the current is the sketch of what we will become' (Deleuze, 2006b, p. 345). Deleuze and Guattari's collective machines are more focused on currents and less so on archives, but there is no doubt that these writers inspired each other. And this is evident in a particularly strong parallel. Both concepts, apparatus and machine, demand a very concrete and specific analysis, they gain significance only in relation to empirical phenomena that are analytically cut from these perspectives. And in researching and analysing collective machines, the analyst should also take forms of subjectification and the becoming of subjects into account.

2.3.4 Is a machinic assemblage an actor-network?

A comparison between ANT and machinic thinking is made difficult by the fact that there is no single version of ANT; rather, it is 'a disparate family of material-semiotic tools, sensibilities, and methods of analysis that […] is not abstract but is grounded in empirical case studies' (Law, 2008, p. 141). ANT has always been a plural approach and many authors have extended and transformed the initial ideas (e.g. Farías and Bender, 2012; Passoth and Rowland, 2010; Law and Singleton, 2005). Further complicating the issue, many authors mention ANT and assemblage theory together or even conflate the two (Anderson et al., 2012). There are, however, important differences between these approaches. Assemblage theory enables one to theoretically address phenomena of social order and disorder that go beyond situated and traceable connections that prominent authors in ANT, e.g. Latour (2005), claim to be the only legitimate phenomena for social inquiry. Machinic thought offers more than a thinking of situated actions and distributed agency that are the focus of Latour, e.g. in his famous studies of how large keys make hotel guests return the keys at the reception or road humps slow down car drivers (Latour, 1992). In the following I discuss particular differences in the details of the conception of relations, in the conception of time and history and in the political sensibilities that can be found in these theories.

ANT and assemblage theory share the orientation towards finding novel ontological understandings of the world in contrast to dominant modern versions of such ontologies. First, they both argue that the world is heterogeneous and relational in character. Entities of different origin and kind, e.g. human, non-human, material, ideational, are formed and transformed within relations that they have and build with other entities. Both ANT and assemblage share an orientation towards heterogeneous and multiple worlds and the concrete analysis of them, instead of referring to grand and general claims such as 'laws' that shape the social.

[25] Rabinow (2011) uses the difference in stability and duration to differentiate apparatuses, as rather stable and dominant from assemblages, as novel, more indeterminate, creative and uncertain. Otherwise, he construes them similarly.

Yet there is an important difference in how entities, relations and processes are being conceived. In assemblage theory, the relations that constitute an assemblage are being conceived as ‘relations of exteriority’, relations that neither completely define nor determine any elements in such relations. Particular elements can move from one assemblage into another without being an entirely different element, but with other capacities of the element being affected (Harman, 2013; DeLanda, 2006). ANT has another conception of relations where an element is either in an actor-network, which for ANT must be empirically observable in its details, or it is not. It conceives of ‘relations of interiority’ where the element is determined by the whole with which it is related. Assemblage, therefore, conceives of ‘outsides’ of and movements between different assemblages, whereas ANT does not allow for an outside of actor-networks.

While this might seem a very theoretical concern, it has drastic consequences for how time and politics are being conceived in each of the theories. Assemblage theory is about ‘becoming’. It conceives of the world as being formed in processes. It is, however, not a world of constant fluidity and novelty that is being conceived but one in which stabilisations and destabilisations of machinic assemblages (understood as processes) take place. Within these processes elements, people, ideas, organisations and materials become as they entwine with particular assemblages and unfold their potentials. Since elements enter relations of exteriority, they are never completely novel when they entwine with an assemblage, but they already have a history and particular historically created characteristics and their becoming also depends on these. Through focusing on becoming, assemblage theory also conceives of history, not as a linear process, but as that which connects what was with what is not yet. In contrast to that ANT thinks in terms of relations that ‘actants’ or ‘actors’ ‘have’ to other elements and how through this they acquire stability and power. The classic studies of ANT, indeed, were concerned with stability, for example how scientific knowledge can travel as ‘immutable mobile’ from the laboratory to policy without losing its ‘truth’ claims. It is highly indicative of this stability thinking that metaphors of ‘fluidity’ and ‘fire’ to denote complex processes were introduced under the label ‘post-ANT’ (Law and Mol, 2001). In classical ANT, however, there is no becoming but the constant co-definition of actors in actor networks, which are conceived as observable relations in the present – what was before or after that is irrelevant[26]. ‘If we wish to lend the term “assemblage” to Whitehead and Latour, we cannot forget that their assemblages [i.e. actor-networks] last for only an instant, perishing in favour of a close successor that is not, strictly speaking, the same assemblage’ (Harman, 2013, p. 125).

Related to thinking history, there is a further important difference that is not so much theoretical, but rather part of the sensibilities and styles of ANT and assemblage writing. Many, if not most, ANT studies are based on microsociological, often ethnographic, case studies that operate within a particular setting and ‘follow the actors’ there. Related to this, Latour (2005) launched grand criticisms of what he calls ‘critical sociology’ that would use theory (e.g., ‘class’, ‘habitus’) to explain ‘the social’ and its struggles, instead of analysing how the social comes into existence in the first place. Instead of explaining, Latour argues, one should describe what is going on. Different to this, machinic thinking in Deleuze and Guattari was strongly inspired through the events of 1968, and it can also be read as a way to renew Marx and Freud by doing away with the idea of a pre-given subject (e.g. an individual actor or the working class) by replacing it through machinic assemblages. Their musings on the ‘rhizome’ that start *A thousand plateaus* (Deleuze and Guattari, 2004) are also thoughts on their novel theory of ‘radical’ thought and action, to move along and to influence social life from within, yet without a superior or privileged starting point or final end.

> ‘Make rhizomes, not roots, never plant! Don’t sow, grow offshoots! Don’t be one or multiple, be multiplicities! Run lines, never plot a point! Speed turns the point into a line! Be quick,

[26] Latour (2005) tried to remedy this with his idea of the ‘plasma’, a field of potentialities beyond empirically observable and for the analyst traceable connections. And although he states that the ‘plasma’ is necessary for any actor-network he excludes the plasma from analysis.

> even when standing still! Line of chance, line of hips, line of flight. Don't bring out the General in you! Don't have just ideas, just have an idea (Godard). Have short-term ideas. […] A rhizome has no beginning or end; it is always in the middle, between things, interbeing, intermezzo. The tree is filiation, but the rhizome is alliance, uniquely alliance. The tree imposes the verb "to be," but the fabric of the rhizome is the conjunction, "and... and... and..." This conjunction carries enough force to shake and uproot the verb "to be." [...] Making a clean slate, starting or beginning again from ground zero, seeking a beginning or a foundation—all imply a false conception of voyage and movement' (Deleuze and Guattari, 2004, pp. 24–25).

In some respects ANT and machinic thinking share the same problems. Yet, as I have shown, in others they differ. I do not think that they exclude each other, especially as they are both not dogmatic systems of theory. Rather, Deleuze and Guattari wanted to create tools for thought that could be used and changed in whatever way. And some of their tools were used in early ANT. And equally I use inspirations from both fields of thought. From ANT I take the great attention to situated details in studying heterogeneous relations. Deleuze and Guattari, although they share the ontology of immanence and concrete analyses, push the analyst beyond a strong empiricism that only takes into account what is present. There are speculative elements to address possibilities, becoming, the virtual and actual, yet without going back to ideas of 'essences' or 'universals'. Furthermore, as discussed before, machinic thinking is a way to bridge the gap between concrete analyses of heterogeneity and classical theories (e.g., Marx, Mumford, Foucault) that are rejected by Latour. The 'rhizomatic' ethics that are argued for by Deleuze and Guattari, furthermore, invite engaged and normative forms of scholarly practice, for an assembling with uncertain dynamics and for ways to argue for and participate in human becoming. In the final section of this chapter I briefly discuss how I split TechKnowledgy into different perspectives as an analytic strategy for the complex processes that are designated with the concept.

2.4 Towards the TechKnowledgy of open digital fabrication

I started this chapter by arguing that 'technology' has to be considered beyond technical objects and that to grasp phenomena such as open digital fabrication the older meaning of the term technology as techno-logy has to be revived and updated. With TechKnowledgy I established a concept that allows one to think about the processes that produce 'technology' and their character. In fact, 'technology' is then to be found in the dynamic interplays and transformations of technical objects and knowledge in different dimensions. TechKnowledgy shifts the perspective towards the question of how heterogeneous elements are being connected to create processes that enable the imagination, invention, exploration, production and usage of technical objects in the first place. Although it is highly important to adhere to the complex and dynamic nature of such processes, there is a need for an operationalisation of this concept for empirical analysis.

The analytic strategy that I pursue draws upon the theories discussed above to focus on different aspects of how 'knowledge' and 'technology' are produced and organised together. The empirical analyses in the following chapters will focus on particular elements and trace and analyse how they connect with and are transformed through collective machines. These elements are technical objects, subjects, organisational forms and desires. Based on the machinic ontology just elaborated, these elements are not considered to be independent and autonomous but themselves produced and enmeshed in various relations. However, they are analytical reductions that help to enter the collective machines under investigation from a particular perspective. They are the different lines that I will follow into the dynamic connections and formations of the collective machines of the two case studies. 'Knowledge' is not amongst these elements, because it is considered to be that which relates these different elements together and is an emergent effect of the collective machine. It will therefore be analysed in different forms in relation to the respective dimensions that are pursued.

Central to the analysis is the dual focus on relational processes of how a particular element is arranged by other elements and how the element arranges others. These are processes that can happen simultaneously and are grounded in the machinic ontology. This also makes it possible to consider a TechKnowledgy to be a set of collectively constructed procedures, although these constructions take place from within already established, constraining and enabling collective machines.

The first case, the Lasersaur project, takes as its starting line the technical object of the laser cutter and looks at its unfolding from it being an imagined object to it being a widely reproduced CNC machine. This mode of analysis will then connect the object to subjects, organisational forms and desires and show how they connect into a dynamic collective machine. The case of FabLabs and FabLab Karlsruhe in particular starts from the line of organisational forms and how different such forms have been mobilised and connected to create and spread FabLabs. Then the chapter shifts towards the line of subjects and how they actively arrange technical objects, desires and organisational forms to shape a FabLab, whilst at the same time being arranged by the wider collective machine of FabLabs. The abstract machine of the TechKnowledgy of open digital fabrication is an analytical result of both case studies and will be summarised in the concluding chapter. The challenge is to identify shared procedures that are visible within the projects and the relations they have to their environments. In the conclusion, I will literally present an 'abstraction' from the concrete manifestations of open digital fabrication. This helps to draw out its key characteristics and the 'logic' that connects the elements in the TechKnowledgy.

3 Lasersaur: opening objects

When I first encountered an assembled Lasersaur in the project founders' home and studio, I was struck by the neat integration of the machine into the living room. Laser cutters are normally found in industrial workshops, in development departments, and some can be found in universities. Laser cutters are typically considered to be tools that cut or engrave different materials; they are means of production. While the Lasersaur is capable of this as well and some versions of it can be found in similar places to normal laser cutters, it is strikingly different to its industrial cousins. To date I have seen three assembled Lasersaurs and many others online. Each of the builds made clear that they are special objects. Edgy yet elegant, the machines show their cables and screws and the aluminium parts of the frame, which all look similar. It is as if the machine is literally 'open' with holes in its surface that present the inside. Instead of hiding them under a neatly designed and closed surface, the Lasersaur presents the objects that comprise it. It shows its relations to standardised industrial objects that helped to turn it into something special. Although the aesthetic design of the Lasersaur is based above all on functional criteria, it departs from mainstream industrial design. Normally, the surface hides the inner workings of objects and suggests that the object is one unified entity (Anusas and Ingold, 2013). With its open appearance, the Lasersaur, even as a stable entity in a room, points at the flows of other objects and work that put it together. And these flows and relations are what makes the Lasersaur an open-source object produced by a particular TechKnowledgy.

The Lasersaur is an open-source object. One of the main tasks of this chapter is to qualify the 'source' aspects and the transformations and challenges such open-sourcing of tangible objects creates. The Open Source Hardware Association defines objects such as the Lasersaur as follows: 'Open source hardware (OSHW) is a term for tangible artifacts – machines, devices, or other physical things – whose design has been released to the public in such a way that anyone can make, modify, distribute, and use those things' (http://www.oshwa.org/definition/, accessed 17.12.2017). The chapter, however, shows in many ways how intricate and complex such 'opening' of a design is and how a specific public is product and producer of the Lasersaur, a public that is inextricably entwined with digital technologies. The chapter analyses what 'open knowledge' in open-source hardware is and how technical objects play a central role in the collective machines of such projects.

The chapter proceeds along three different yet related steps. First, I argue that technical objects are the foundation for projects like the Lasersaur. This is contrasted with the only marginal attention that objects have received in social science and in research on open-source practices. I show, however, how objects make open-source projects possible and discuss the necessary theoretical resources to analyse the Lasersaur project from this perspective. Second, I analyse the social dynamics of the Lasersaur project from a chronological point of view, to understand how the project's biography entwined with objects. Third, I change this linear perspective towards four different complex sets of relations that are central to understand the Lasersaur as a multiple object which exists in different forms and in different relations to people and objects in its environment. I end the chapter with a discussion on the importance of particular technical objects for the TechKnowledgy of open digital fabrication.

The materials that help me trace and analyse the Lasersaur project are varied and multidimensional. The analysis is based on three different sets of data: qualitative interviews with key figures in the project; an analysis of the project's many websites and other Lasersaur-related content on the Internet; and my participant observation of a building process of a Lasersaur in FabLab Karlsruhe. Each of these reveals different aspects of the project and the chapter tries to make these different paths to the project visible by changing the style of presentation, foregrounding different relations that the object affords. This entails relying on my perspective and relation to the object at times. This mode of presentation is complemented with the digressions already used in the chapter before to embed the analysis into wider dynamics. To set the ground for the empirical analysis, however, the discussion on technical objects and their changing relations due to digitisation has to be continued.

3.1 Open-source objects

Extremely condensed, the history of the Lasersaur reads like this: two young artists with a background in open-source software wanted to have a laser cutter. Unsure of the actual feasibility, they released their intention to build an open-source laser cutter on the Internet. About 200 people were interested, and supporters joined a mailing list. Despite very limited resources, a first prototype was cutting eight months later. Three years later, about 150 such machines, further developed than the prototype by the community, could be found around the world. Accordingly, the Lasersaur, even as a vision or thought object, was the object around which the community began to form. Objects, as this chapter will show, are an enabler of the open-source culture, at the heart of which is the collaborative production, circulation, use, contestation and control of objects and the knowledge about them.

This can be further exemplified with one of the founding myths of free software – an important precursor in terms of practice and discourse to open digital fabrication: Richard Stallman, the founder of the Free Software Foundation, used to share software code within his network of computer programmers and hackers. However, with the advent of neoliberalism intellectual property rights tightened around 1980 and corporations increasingly monopolised software code. Later, something went wrong with a printer at MIT that Stallman and his colleagues used. Stallman wanted to change the printer's software, yet was neither allowed nor enabled anymore, since the printer manufacturer restricted access to the code:

> 'I had already experienced being on the receiving end of a nondisclosure agreement, when someone refused to give me and the MIT AI Lab the source code for the control program for our printer. (The lack of certain features in this program made use of the printer extremely frustrating.)' (Stallmann, 2010, p. 9)

Stallman, however, was used to sharing software code in networks of computer scientists during the years before companies started to become more restrictive (cf. Kelty, 2008). The printer and its protected software code has become a central object in the founding story that Stallman tells about why he started to think about ways to 'free' software from intellectual monopolies of companies. The 'Free Software Foundation' and the GNU operating system, which was created by Stallman, has been defining and championing four freedoms ever since:

> 'The freedom to run the program, for any purpose (freedom 0). The freedom to study how the program works, and change it to make it do what you wish (freedom 1). Access to the source code is a precondition for this. The freedom to redistribute copies so you can help your neighbor (freedom 2). The freedom to distribute copies of your modified versions to others (freedom 3). By doing this you can give the whole community a chance to benefit from your changes. Access to the source code is a precondition for this' (Stallmann, 2010, p. 3).

These freedoms emphasise individual actions and transactions between people, and much research has similarly focused on the 'ethics of hacking' (e.g. Coleman, 2012; Himanen, 2001) that normatively structure these actions. Yet the objects of such actions – in this case software programs – are only marginally addressed in this narrative. Although 'access to the source code is a precondition' for these freedoms, the software and the infrastructure it depends upon remains in the background. It is extremely significant though that the idea and culture of free software were born in a research environment where the printer was no longer modifiable amongst all kinds of technical objects that are typically modified in a technical university. 'Hacking' as a particular form of such modifications can also be traced back to technical universities after the Second World War (Coleman, 2012; Kelty, 2008). Accordingly, Stallman's struggle for free software is as much a struggle for particular characteristics of objects as it is for sharing and transparency (two important values in research, a social field that is also very important for the Lasersaur).

Most of the research on open-source practices, however, has not addressed technical objects in a depth that equals their importance for the phenomenon. This research, furthermore, has focused almost entirely on open-source software. Although the lines mix, one can discern certain core themes. One important strand focuses on 'hacking' as a value-laden cultural practice and writes about the ethics and aesthetics that sustain it. The 'hacker' is at the core of this perspective (Coleman, 2012; Coleman and Golub, 2008; Jesiek, 2003; Himanen, 2001; Moody, 2001; Levy, 1984). Closely related to this approach is research that focuses on open source as a practical critique of intellectual property regimes and hackers performing such a critique. Open-source projects depend on and promote knowledge as a 'commons'. This is contrary to the logic of intellectual property regimes, which constitute a mechanism to exclude people from knowledge as a private property, and therefore make it 'scarce' through legal means. The famous 'copyleft mechanism', invented by Stallman and legally ensured through open-source licences, is symbolically and practically an inversion of copyright by copyright's means to help keep knowledge in the public domain. It demands that changes to software published under a copyleft licence have to be published under the same licence again (Söderberg and Daoud, 2012; Stallmann, 2010; Hardt and Negri, 2009; Berry, 2008; Wark, 2004; Weber, 2004). Then there is a lot of research which investigates the novel forms of organisation of open-source projects, the motivations of participants and the internal governance of the projects. Often related to the importance of knowledge as a commons in open-source projects, it is claimed that open source constitutes a new mode of production based on voluntary action, different to markets and hierarchies (Benkler, 2013, 2006; Feller et al., 2005; Tkacz, 2015; Ghosh, 1998; Lakhani and von Hippel, 2003; Raymond, 2001). As discussed before, however, such claims of open-source practices as beyond capitalism no longer work. Instead, there is a huge diversity of organisational forms of open-source projects (Schrape, 2016).

I argue in this chapter that it is not simply 'access' to objects that is central to the TechKnowledgy of open digital fabrication but particular ensembles of technical objects and their characteristics that have emerged within sociotechnical infrastructures during the past decades. These enable particular forms of access and modification to objects. Without these objects there would be no 'open-source' practices. Simondon (2012, ch. 1; 2016, ch. 1) argues that standardised objects are not the results of industrialisation, but that industrialisation was the result of the possibility of standardised objects. Such a recursive logic is central to open source as well. As Edgar Morin, a preeminent complexity thinker, puts it, in recursive causality 'the effects and products are necessary to the process that creates them. The product is producer of that which produces it' (Morin, 2008, p. 61). Open-source objects and related objects with similar characteristics produce the projects that produce them.

Recursivity is also a key insight in one of the classic studies on free software. Kelty argues that free software is a 'recursive public' which 'is vitally concerned with the material and practical maintenance and modification of the technical, legal, practical, and conceptual means of its own existence as a public' (Kelty, 2008, p. 3, italics omitted). Such a recursive public creates and maintains its own sociotechnical infrastructure: 'the Internet', which in its early days was closely related to free software (Benkler, 2013; Castells, 2002). Accordingly, Kelty argues that participants in free software 'express' their politics in discursive ways and through the creation of technologies (software, networks), which in turn enable or stabilise the recursive public. Kelty's grand claim about the close interrelation of Internet and free software, however, has to be viewed with caution nowadays. 'The Internet' has changed and is far different from the early 1990s when free software practices might have been central to it. In a recent text, Kelty (2013) admits that 'recursive public' might no longer be a useful concept to understand the contemporary constitution of open-source practices. Repeating a key argument of his 2008 study, Kelty states that the 'cultural significance of free software' lies in its transformations, as the practices that constitute it are modified or enter other cultural domains. And there have been many transformations during the last years – such as the emergence of open-source hardware. For Kelty there have also been many negative transformations, mainly the pragmatic uptake of open-source software by huge corporations such as Google and Facebook. According to Kelty, they rip the democratising and empowering aspects off this phenomenon and increasingly monopolise the formerly decentralised infrastructure of the Internet. Yet he sees the liberal ethic of free software entering into protest movements and counter-cultural experiments such as FabLabs and hackerspaces. In this contemporary plurality of open source new ideas are needed. 'What we lack—scholars, activists, developers, lawyers alike—are concepts appropriate to this phenomenon' (Kelty, 2013 n.p.).

Part of such a reconceptualisation must be an inventive attention to objects. Research on open-source practices, however, mirrors the social sciences more generally, which have largely excluded 'objects' from their investigations of social life and instead focused on intersubjectivity and communication (Latour, 2005; for critiques of this exclusion: Eßbach, 2001). Of course, 'objects', 'materiality' and 'things' have started to enter the descriptive and analytic toolkit – not least due to the success of STS since the 1980s. When talking about globally dispersed and multiple objects such as Linux or the Lasersaur, however, we need a better understanding and conceptualisation of what such objects are and how they come to work in certain ways. Only recently, efforts for a dedicated 'object-oriented sociology' came into being (cf. Law, 2002; Lash and Lury, 2007; Marres, 2012)[1]. The approach pursued here joins these efforts and aims for a conceptual level that is appropriate to the complexities of open-source objects.

MacKenzie (2005) in one of the rare studies of objects in open-source practices argued for the centrality of software objects. He claims that the circulation and transformation of the coded object Linux is performative of the 'collective agency' of the project. 'As an operational object serving as a platform, Linux quite literally co-ordinates the circulation of specific social actions [...]. At the same time, co-ordinated actions centred on Linux constantly modulate it as an object in self-referential ways' (Mackenzie, 2005, p. 77). Furthermore, circulations of Linux through different technical, industrial and cultural domains enact the object as something that is multiple, yet one – Linux actually is a lot of 'Linuxes' that nonetheless somehow adhere to each other (see for an ontological argument about the multiplicity of objects: Law, 2002). maxigas (2015, 2016) has also foregrounded the role of what he calls 'unfinished artefacts' in the engineering culture of hacking. Such artefacts are the core of the hacking culture, since they constitute hacker projects, the focus of hacking. Unfinished artefacts are often constantly modified, documented, reproduced, admired or joked about and are, thus, never really finished but evaluated by hackers as processes and not as finished products, like capitalist firms would typically do. maxigas further argues that hackers create unfinished architectures, i.e. organisational forms, that enable the work on such unfinished artefacts and the collective culture of hacking that centres on them. Unfinished artefacts and architectures depend on each other.

In this chapter I further extend such perspectives on technical objects and address the specificities of open digital fabrication objects. These, however, are based on an object-historical change based on digitisation which goes beyond open source and has transformed significant aspects of the object worlds people encounter in their lives. What did that change involve?

[1] In philosophy, the recent movement of 'object-oriented ontology' similarly aims to find key properties of objects and their inter-objectivity (e.g. Morton, 2013).

3.1.1 Digitsed technoecologies

Free software in the 1980s was already construed upon the ontologies of digital technologies and software. By then, digital devices and programs had already entered the worlds of research and business. Digital technologies were at that time perceived as harbingers of a new technological era. The novel digitised infrastructures provided a sense of a new technical realm that is highly malleable, mobile and powerful (Turner, 2006; Castells, 2002). Software was perceived and experienced by computer scientists like Stallman to be the eminent route into an 'information society' and that it needed to be 'liberated' from old powers to bring about this new society (Söderberg, 2013b). However, software and computers were not only framed in particular ways but also formed the technical basis for particular knowledge productions. While at the beginning free software programs were stored and exchanged on material objects, disks and the like, the Internet added new forms of transmission of digital information and code. Its network of computers constitutes the means of production and exchange of code in open-source or free software projects, and it allows for communication. Software in such networks is from a technical point of view easily reproducible at almost no cost. Software connects machines and people globally (Berry, 2012; Kitchin and Dodge, 2011). It is easily multiplied, moved about and shared. Actually, this aspect of digital information technology has proven to be a driver to debates about novel 'information economies' that challenge particular configurations of intellectual property (Mason, 2015; Rifkin, 2014; Söderberg and Daoud, 2012). As Gorz writes emphatically: 'Everything translatable into digital language and reproducible or communicable at no cost tends irresistibly to become common property [...] when it is accessible to – and useable by – everyone' (Gorz, 2010b, p. 11).

Yet, despite the technical properties of software, a central question is still how the explicit knowledge that is transmitted through software is made accessible and usable, or not. Furthermore, in comparison to software the partly tangible objects of open-source hardware are in important ways 'offline' and recalcitrant. They are enabled by more than computer networks, and they constitute a need to translate their 'materiality' into the 'immateriality' of information in these networks. It is, however, the specific alignments of 'material', 'immaterial', 'analogue' and 'digital' aspects of technical objects that is producer and product of open-source hardware projects such as the Lasersaur. I argue, however, that there are particular qualities in digital infrastructures that are significant conditions of possibility for open-source hardware projects and the technical objects in the centre of them. This discussion extends the arguments about the relationship of technical knowledge and technical objects in TechKnowledgies.

As discussed in the chapter on TechKnowledgies, Simondon argued that large cultural changes are entwined with changes in technical objects and their constellations and in the relations between humans and such objects. Amongst the most significant object-historical changes in the past decades has been the emergence of the Internet, also a networked infrastructure, which vastly extends the possibilities for connectivity beyond what Simondon had in mind when he wrote about open objects. To get to the specificities of the digitised object constellations that are of central importance to open digital fabrication I draw on the media philosopher Hörl (2013b, 2013a), who extended Simondon's thoughts on open objects and the growing indeterminacy of technical objects and their relations to think contemporary 'technoecologies'. Central to Hörl's thought is the notion of ecology, which according to him has expanded in meaning to go beyond natural systems – this complements the machinic thinking of Deleuze and Guattari, which is also based on ecological conceptions. Nowadays, people in technologised societies live within technoecologies based on complex relations between humans and objects, distributed forms of agency – that is no longer confined to humans alone – and inter-objectivities. In particular, Hörl argues, digital objects play a key role in these novel technoecologies[2]. He describes the digital open object ecologies in the following way:

> 'This entails the acting and self-acting […] object-cultures […] which are more and more migratory or submerged within our environments, informing our infrastructure, processing the backgrounds of our being and experience with the highest computational intensity, operating in new, micro-temporal regions, and which are shaping the face and the logic of contemporary cyberneticization' (Hörl, 2013a, p. 124).

Within these technoecologies not every object is an open object. There are many examples of non-connectivity, exclusions, secured channels, lack of interoperability and malfunctioning in digitised object worlds. However, in culturally significant ways digital open objects have come to play a central role. The Internet, software and computing devices have brought about a drastic increase in open objects which are modifiable, connectable and, therefore, increasingly indeterminate.

Within such digital technoecologies, according to Hörl, fundamental conceptions of subject and object, agency and interaction are drastically changing. Related to these, and central to this study, the conception of technology is changing as well. Hörl (2016) argues that within the digitised technoecologies technical objects are acting and interacting in significantly new ways. Instrumental conceptions of technology that conceive of subjects as users of tools are no longer appropriate. Rather, acting subjects have to be conceived as within technoecologies where other entities are acting and enabling action as well. The digitised technoecologies have been quickly spreading and growing, in the process entwining with other technological spheres, which might have followed other principles of control and communication[3].

This process, which is also mediated and engendered by subjects, is an important dynamic for the possibilities and motivations of open-source hardware projects. The interconnectivity, fluidity and malleability of digital open objects has become a model for open-source hardware objects such as the Lasersaur. The 'openness' of these digital object networks informs and fosters the openness of the tangible objects. CNC machines such as 3D printers and laser cutters form the symbolic centre of open digital fabrication. They produce material objects by translating digital forms into the machinic forming of materials. These processes, which also require at least a PC and suitable software, enable people to conceive material objects digitally and to realise material objects. Many of the technical objects in open digital fabrication are furthermore 'open hardware objects'. Culturally this designates the historical resonances and continuities these objects have with 'open-source software'. On an ontological level, however, this notion shows how tightly coupled with software these objects exist. They are defined as the 'other' to software – soft vs. hard. Yet from our desktop computers we also know that there is no software without hardware; software runs on hardware and hardware only has a purpose if it is manipulated through software. Phenomenologically speaking we could not distinguish a soft sensation if there was not also a hard one. There is also a revaluation of knowledge towards the knowledge necessary for manipulating digitised objects instead of the knowledge of manipulating material objects manually. Open-source hardware takes the manipulation of digitised explicit knowledge further as designs, files and software are publicly circulated on the Internet for others to download, use and modify. Therefore, the existence of open-source hardware and even 3D printing and digital fabrication depends on the ontological layer of digitised technoecologies.

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2 See for further explorations of this digitised and networked world: Serres, 2015; Urry, 2014; Kitchin and Dodge, 2011; Thrift, 2004, 2011; Stiegler, 2010; Flusser, 1999.

3 A speculation of Deleuze and Guattari on the qualitative changes through digitisation resonates with Hörl's thoughts: 'If motorized machines constituted the second age of the technical machine, cybernetic and informational machines form a third age that reconstructs a generalized regime of subjection: recurrent and reversible "humans-machines systems" replace the old nonrecurrent and nonreversible relations of subjection between the two elements; the relation between human and machine is based on internal, mutual communication, and no longer on usage or action.' (Deleuze and Guattari, 2004, p. 458)

In the next part I turn towards the empirical analysis of the Lasersaur project and analyse its history within technoecologies that enabled and produced it. This is then also an analysis of the TechKnowledgy that was product and producer of the Lasersaur project. How was the Lasersaur produced, used, transformed, combined, circulated, known, imagined or contested, and how did other objects participate in or even enable this? In turn, how has the Lasersaur been unfolding? How did object and project recursively form each other, how did the collective machine emerge within a dynamic technoecology?

3.2 Assembling a development project

In this part, I analyse the history of the Lasersaur project and am particularly interested in which forms of organisation and organisational support the project engendered and how objects played a role in enabling and mediating such organising. After clarifying my empirical strategy I turn to how desire for the Lasersaur was created and how an unfolding machine entwined with an unfolding project.

In May 2013, I interviewed Addie and Stefan, the Lasersaur's founders, in their studio apartment. This is also where most of the development work for the Lasersaur took place. Next to us during the two-hour interview, neatly integrated into the room, stood the reference machine of the Lasersaur project. Afterwards the two showed me the basic functions of the laser cutter. In our interview we covered their perspective on the Lasersaur project's history and future, the community and the open-source culture more generally. They also pointed towards Tom and Mark, the two other interviewees, since they played special roles in the project[4]. Tom is the builder of the third Lasersaur, the first one that was built without Addie and Stefan. He is head of a non-profit association for the education of children called 'Piloten' and is working as an industrial designer. The interview covered the association's mission, his involvement in the Lasersaur and his observations of the open-source culture. Mark is the director of a design institute called 'Fabrik 2'. With a residency the institute supported Addie and Stefan and the further improvement of the Lasersaur's design to a great extent. In our interview we talked about the institute, the Lasersaur project and his interpretations of the open-source culture. Later on, I will further describe the interviewees and the context they are working in.

The other empirical material for my study should not be underestimated in relation to the interviews. The Lasersaur project's reality is to a large extent on the Internet and most of it is publicly available there. There is the Kickstarter website that initiated the launch of the project, there are many interviews (text or video) with Addie and Stefan, there's the project's website and the public mailing list. Furthermore, there are many videos of builds of Lasersaurs by different people or organisations and websites devoted to the individual building projects. All of these informed my analysis and interpretation of the project. To give a sense of the realities of the Lasersaur, I try to mix the empirical material when appropriate to the argument. And I highly recommend my readers to go online and check out the links that I reference in the text. This way one can get a direct phenomenal impression of central elements in the project's machinic assemblage.

[4] All four interviewees gave their consent to the use the interviews and to making direct reference to their identities. Since the project's specificity as a laser cutter is highly important to understanding it and Addie and Stefan actively link themselves to the project in public I decided to use their names and the direct reference to the Lasersaur. Nonetheless, I changed the names of the other interviewees to Tom and Mark and of their organisations to Piloten and Fabrik 2 to provide a high degree of anonymity. The atmospheres of the three interview situations were very positive and based on mutual interest. The interviews took place where the people work and use the Lasersaur and lasted one (Mark) and two and a half hours (Addie and Stefan, Tom). I recorded and transcribed the interviews and analysed them in a qualitative and interpretative manner. With an overview of the interviews I decided to not conduct further interviews, since I gathered three different perspectives of people who have known the project from an early stage onwards. And since my focus here is not on different interpretations of the project, but on the conditions of possibility of its realisation, these three interviews provided enough heterogeneous material to complement my other empirical observations.

There is, however, a third field of empirical enquiry. As the co-founder of FabLab Karlsruhe, an open workshop that makes 3D printing and other CNC machines publicly available, I have been in close contact with open-source objects. Furthermore, in autumn 2014 a Lasersaur was built in and for the FabLab, and I participated in the building process. As Ingold argued, making is a form of participation in a world of becoming and therefore a proper method for human and social sciences (2013). Besides the observation of the group, the participation in the making of the machine was a close and revealing empirical encounter with this object.

3.2.1 Desiring the Lasersaur

For the founding of the Lasersaur project it was first necessary to bring the desire for such a machine into being. I analyse how this desire assembled in Addie and Stefan in exchange with their environments and how they set up an online platform to socialise this desire for the machine to turn it into the starting point for the project. I argue that this is a form of collectively shaping desires in which a particular vision of a future – that of a future with open-source laser cutters – is being produced as desirable and feasible. In this process, organisations, organisational forms and other subjects play a role to form a machinic assemblage that engenders the collectivisation of this desire and becomes a 'desiring machine' that changes connections and engenders a process of becoming. In the second chapter on TechKnowledgies I already discussed how imaginations of technoscientific futures play a crucial role in legitimising and shaping collective machines. How did such shaping of desires take place in relation to the technical object of the laser cutter?

A good start to follow the Lasersaur's becoming – and the preparation for its desiring – is in New York around 2006, decades after laser cutting was first applied in industrial settings. Addie and Stefan, the future founders of the Lasersaur, were studying in the 'Interactive Telecommunications Program' of New York University, where students 'explore the imaginative use of communications technologies'[5]. This is not only a programme with lecturers such as Clay Shirky who promote emancipatory ideals in relation to the Internet (Shirky, 2008, 2010), but also a place where research and development with new media (i.e. technical objects) takes place; an environment tightly connected with open objects. They graduated with an open-source hardware multi-touch system (roughly similar to touch screens of smartphones) and were already experienced with open-source software, but had not had a central role in a larger collaborative group as later in the Lasersaur project. They were active in and supported by the thriving nexus of art, technology and open-source culture in New York, e.g. at 'Eyebeam'[6]. And they were working with laser cutters for their own creative projects. In 2006, they started their studio 'Nortd Labs' as 'a collaboration based studio of creative thought that engages science, art and design [and that believes that] people should collaborate globally and build locally' (labs.nortd.com/about, accessed 01.04.2014). When they moved away and became self-employed artists/designers/technologists in 2009, however, they neither had access to laser cutters and other equipment nor the presence of a strong hacking, making, art and science community any more. Without this equipment, Addie and Stefan wanted a laser cutter as a tool and quickly accepted that industrial machines with prices of tens of thousands of euros were out of financial reach for them. Inspired by their former work and confident in their technical abilities, the two began thinking about building a laser cutter themselves.

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[5] 'ITP is a two-year graduate program located in the Tisch School of the Arts whose mission is to explore the imaginative use of communications technologies — how they might augment, improve, and bring delight and art into people's lives. Perhaps the best way to describe us is as a Center for the Recently Possible'. (http://itp.nyu.edu/itp/, accessed February 2013)

[6] 'Founded in 1997, Eyebeam was conceived as a non-profit art and technology center dedicated to exposing broad and diverse audiences to new technologies and media arts, while simultaneously establishing and demonstrating new media as a significant genre of cultural production'. (http://www.eyebeam.org/about, accessed February 2013)

Ambient machine: the maker movement

The Lasersaur project can be considered an element in a much wider and diffuse machinic assemblage: the 'maker movement'. The term 'maker' in its present connotation was popularised by O'Reilly Media, a company specialised in publications concerning (open source) software, with the launch of their 'Make Magazine' in 2005. The rhetoric strategy behind the magazine's title was to address more people than with the more narrowly and partly negatively interpreted term 'hacker'. Yet, far from mere semantics, the magazine has been including all kinds of DIY projects, which do not only feature computers and electronics, the main fields for tinkering of hackers. And the company even started a successful series of 'maker faires', lare events in the US and beyond about all forms of DIY, combining commerce, hobby and festival (see the CEO of O'Reilly describing the history of Make Magazine: http://vimeo.com/51841691, accessed 25.06.2014; see also this press release for a further self-description of Make: http://www.oreilly.com/pub/pr/3185, accessed 25.06.2014).

In my interpretation, Make Magazine successfully participated in the emergence of an assemblage that was happening anyway: the spread of Internet supported DIY practices and the transformation of hacking and open-source cultures. Around the same time, successful open-source hardware projects were launched as well. And in an even wider perspective there has been a growing trend towards 'prosumption' in many areas, especially due to Internet-related practices (Ritzer et al., 2012). The maker movement builds upon cultural framings of 'web 2.0' that see a new society of decentralised and networked prosumers being born (Dickel and Schrape, 2016). What has been termed the 'maker movement' could also be seen as a combination of the 'hacker ethic' (e.g. Himanen, 2001) of constructing and tinkering, sharing and learning with an increased diversity of the objects involved: beyond software and electronics 'everything', e.g. textiles, wood, machines, social problems in 'hackathons' (thanks to Carolin Thiem for this hint), can and should now be 'hacked', which also implies that 'everyone' who tinkers can become a 'maker'.

By now, the maker movement is an umbrella term for all kinds of practices and ideas ranging from dedicated open-source practices to DIY as it has been taking place for decades, which are now tied together as a 'movement'. Some exaggerating 'visioneers' (McCray, 2012) already herald the maker movement as a sign of a next industrial revolution (e.g. Anderson, 2012). Yet 'maker' does not only succeed in its prominence due to US companies and intellectuals. 'Maker' also resonates with older discourses of the creative and productive individual, powerfully inscribed into modernity, often as a romanticised antidote to industrial and bureaucratic realities. And more mundanely, it resonates with people simply enjoying making stuff for themselves or together (e.g. Gauntlett, 2013).

Addie and Stefan have played a crucial role in the design *of* and *with* the Lasersaur project. But they did not only design a technical machine, as classical industrial designers or engineers would do, they co-designed a social development and design project centred around the technical object Lasersaur. As Stefan put it: 'I guess there are two things we did. It's, you know, we developed the technical thing, the reference design, and the other thing is sort of, you know, develop the community' (Addie and Stefan, transcript, p. 19). Such multidimensional design and/or organisation of a whole process is central to the project that rather quickly transcended the two initiators. How did that happen?

Around the same time when the idea to build a laser cutter came up, friends of Addie and Stefan launched Kickstarter.com, one of the first and now very prominent 'crowdfunding' websites. The fact that the two spoke about their 'friends' who started a by now successful Internet company signifies their involvement in social networks in which an 'entrepreneurial' spirit and the exploration of the potentials of digital technologies was present. Crowdfunding started mainly with artistic projects that could be supported financially by anyone before their realisation. The goal is to let the 'crowd'1 fund certain projects with small to medium amounts of money for an individual (starting from around 1 dollar) that add up to larger sums. Curious about crowdfunding, yet unsure what would happen, Addie and Stefan put their idea of building an open-source laser cutter on Kickstarter in May 2010 (https://www.kickstarter.com/projects/nortd/lasersaur-open-source-laser-cutter-0, accessed 08.02.2014). By July 2010, 260 people had signed up to support the project and pledged 20,000 dollars to it. In our interview, Addie said that this was

> 'exciting but it was also like this oh fuck stage, because it meant that we actually had to do it! So then it was like, it became real, I feel like, at that point when we got all these backers and people got excited about it; and we saw that there were other people wanting to do it' (Addie and Stefan, p. 4).

The project became 'real' as a social project with mutual expectations and a shared vision. This is a prime example how 'postsocial' intersubjectivity with its desires for unfolding technical objects works, objects that 'structure desire' of subjects and collectives (cf. Knorr-Cetina, 1997). However, this also shows that sticking with the lifeworld of Addie and Stefan would not go far enough to understand the Lasersaur. Kickstarter shows the need for an analysis that is capable of dealing with heterogeneous relations (across time and space), emergent effects and processes. Seen from this perspective the 'oh fuck' is actually one of the first emergent effects of the collective machine that has started to form the Lasersaur project. As Deleuze and Guattari would say, it is not the feeling of Addie, but a 'collective enunciation' of the assemblage. With the object and project acquiring a social existence, the Lasersaur attains relative autonomy from Addie and Stefan – which has steadily increased from here onwards. The Lasersaur was no longer an object constituted by a subject, as typical modern reasoning would have it, e.g. in the figure of the inventor who invents an object. Rather, the reverse has taken place: the Lasersaur started to constitute its subjects, Addie and Stefan and the other project supporters. The Lasersaur has become a 'quasi-object' in Serres's terms. Serres gives a nice example of this idea of relational object thought where the ball is the enabler of the football game and, thus, of intersubjectivity. 'The ball isn't there for the body; the exact contrary is true: the body is the object of the ball; the subject moves around this sun. Skill with the ball is recognized in the player who follows the ball and serves it instead of making it follow him and using it' (Serres, 1982, p. 226). With the Lasersaur having become an object on a digitised social media platform, it started to mediate those who were 'playing' its game. How did the machinic assemblage enable such a 'quasi-object' in the first place?

The Kickstarter experiment is quite telling about the qualities of the Lasersaur assemblage and, therefore, I show how this initial collective machine was composed. Although the desire for the object was created in material environments that lacked a laser cutter, the crowdfunding shows how the constitutive sociality of the project is being created by a specific formation of the digitised technoecology. There were Addie and Stefan who, enabled by digitised technoecologies, produced texts, images and videos that they uploaded to the Internet and its network of PCs that enabled their circulation in digitised form. And there was the structure of Kickstarter, which links the circulation of money to the circulation of the vision of the project and moves this around as it affords a particular public, the audience of Kickstarter projects, who are presented the vision of the project as a digitised set of objects. Publics are based on performative circulations (cf. Warner, 2002). Lasersaur was socialised in a particular mode of digitised circulation enabled at first by Kickstarter, which from then on would define much of the process that constituted the project. But what exactly started to circulate at first?

The project description and vision on Kickstarter read as follows: 'We believe we are able to design a laser cutter that can be built for under 5k (a 100W version) [...]. It would be completely open source and repeatable.' Besides their plan to design the machine the 'rewards' for backers already give a hint as to how Addie and Stefan imagined the project. For example, 24 people pledged $512 each to get an 'Alpha Kit' that promised: 'Get Alpha Access PLUS a super limited edition kit with all the parts to make a laser cutter from motors, frame, and laser!' (http://www.kickstarter.com/projects/nortd/lasersaur-open-source-laser-cutter-0, accessed 14.02.2014). Although it was still rather vague, an initial ‘coding’ of the machinic assemblage took place. The discursive references to ‘open source’, ‘making’ and to making a design ‘accessible’ and ‘repeatable’ at low cost designated the Lasersaur as a project within the ‘maker movement’ and the open-source sphere that aims to empower people by giving them access to tools – a powerful trope in this culture.

On Kickstarter, Addie and Stefan link this empowerment in an analogy to the rise of personal computers:

> ‘Remember when people couldn’t make their own videos, CDs or print out photos? Me neither (at least we try to forget). In many areas of media, the last century was quite the read-only culture where a few gatekeepers would sit on the means to produce everything. Not the best situation for creativity or for people with lots of cool ideas but no cash. When you look at robotics and fabrication this is still the case’ (https://www.kickstarter.com/projects/nortd/lasersaur-open-source-laser-cutter-0, accessed 14.02.2014).

Lasersaur is discursively integrated into the wider vision of ‘personal fabrication’. Similar to the PC, digital fabrication is seen to democratise production and unleash a new age of creativity. This is the key argument in the vision of digital fabrication made popular especially by Neil Gershenfeld, the founder of the FabLab movement (Gershenfeld, 2005), whose discursive framing of CNC technologies is analysed in depth in the FabLab chapter.

Ambient machine: CNC and CAD – from industry to living room

Digital fabrication is partly entwined with two other machinic assemblages that have been shaping the manufacture of objects for some decades now. The first is automation technology, so-called computer numerically controlled (CNC) machines, which have been entering factories from the middle of the 20th century onwards. These machines, as David Noble showed, originated in military research and were not simply a way to make machines more efficient; these technologies have also been used by management to break organised labour and deskill workers (see also Söderberg, 2014; Noble, 1984). The computer control, which quickly and precisely reshapes what the machine does, is central to digital manufacturing as well. Closely related to CNC is the emergence of computer-aided design (CAD), which started as a way to support technical drawings and turned into the complex composition of three-dimensional models of constructions. Nowadays, CAD is central to many technology-developing professions (Peddie, 2013).

Yet these two assemblages go beyond industry and its technologies. Many technosciences such as nano technology, which aims to shape matter ‘atom by atom’, or synthetic biology, which wants to engineer organisms from bits of DNA, are built upon the imagined and partly practical possibilities to design matter with the help of computers, models and machines. Eric Drexler’s ‘nano assembler’ is a visionary predecessor to the vision of digital manufacturing, a machine that produces any kind of tangible object from atoms – similarly the ‘replicator’ in Star Trek produces any object one wishes (McCray, 2012). There is a coming together and mixture of matter and controlled digital information thanks to simulations, machines and cultures (Harari, 2016; Milburn, 2010). Certain technosciences share a key ingredient that reappears in open digital fabrication: the potentials of such computer design are at least as important as the already realised practical possibilities of these technologies.

Crucial for the history of the ‘maker movement’ and especially for open digital fabrication has been the machinic assemblage of open-source 3D printing. This ‘started’ with the RepRap project in 2005 (http://en.wikipedia.org/wiki/RepRap_Project, accessed 14.04.2015) and dramatically changed what 3D printing actually meant (Dickel and Schrape, 2016; Tech et al., 2016; Camille Bosqué, 2015; Moilanen and Vadén, 2013; Söderberg, 2013a; Ratto and Ree, 2012). The project started after a patent on ‘fused deposition modeling’, which was registered in the 1980s, expired. This is one of many technologies used for 3D printing, which adds small layers of heated and docile plastic on top of each other *to create three-dimensional form. Drawing on the open-source approach and a strong vision to make technology self-replicating, the project has created a large community and is definitely one of the main projects of open-source hardware. RepRap dramatically lowered the cost for the creation of 3D printers. Besides this economic aspect, RepRap also pulled 3D printing out of industrial contexts, where it had been used from the 1980s onwards. With RepRap, 3D printing has become enacted as radically networked, open source and as a technology for personal fabrication (instead of 'rapid prototyping' in companies). By now the collective machine of open-source 3D printing also includes commercial versions (some open source, some not), many of which are based on RepRap designs, which all benefited from this initial opening of this culture and market by RepRap. Unfortunately, the difference between this path of 3D printing and industrial 3D printing is often overlooked by commentators. The recent hype about 3D printing (around 2012 in Germany) was strongly fuelled by open source since this not only showed the 'technology', but also the new 'social' formations that entwined with it (Alvial Palavicino, 2016): 3D printing had become the meeting point of decentralised and open Internet cultures and novel forms of material fabrication. Now, with PCs being a part of homes and machines such as 3D printers and laser cutters becoming available to people outside industry and research, CNC and CAD also partly change their shapes.*

Vilém Flusser argued that information technologies radically transform the way we give form to things, they vastly reshape how we relate to and imagine the material world, which has become a project rather than a given: 'the "burning issue" is therefore the fact that in the past […] it was a matter of forming the material to hand to make it appear, but now what we have is a flood of forms pouring out of our theoretical perspective and our technical equipment, and this flood we fill with material so as to "materialize" forms. […] now it is a question of making a world appear that is largely encoded in figures, a world of forms that are multiplying uncontrollably. In the past, it was a matter of formalizing a world taken for granted, but now it is a matter of realizing the forms designed to produce alternative worlds' (Flusser, 1999, p. 28).

These alternative worlds are produced under the condition of networked digital technologies and their entwined cultures; they are products of technosocial collectives that change the way in which form is given to technology and that are experimenting with fully realising the forms that come into existence digitally. In the promise of digitally formed objects lies the promise of reformed socialities.

Making the project public via Kickstarter and funding it that way had another 'coding' effect which is not simply discursive but rather economic or monetary. Kickstarter enabled the collection of money as a form of support in economic and symbolic terms. On the surface, there was money adding up to fund the project on Kickstarter. Yet, this adding up of money that was being visualised by the website also showed how a group of supporters was growing, how an initial project community was emerging. People literally made an 'investment' in the object which still was the vision of something to emerge in the future. Addie and Stefan told me, however, that the money accumulated on Kickstarter was important, but that the most important outcome was the publicity for the project and the group that formed.

In Deleuze and Guattari's terms, Kickstarter 'territorialized' the project by enabling an initial form of intersubjectivity based on the data streams, texts, images and communications that Kickstarter produced and collected at a central place. Kickstarter embodies the idea that the diffused, decentralized 'crowd' of the Internet can gather and create powerful effects based on small individual contributions that add up. This is an idea that is also embodied in mailing lists or wikis, the first of which is very important for the Lasersaur. This principle is also a driver of the open-source culture. Kickstarter enabled the group to communicate and interact with comments or messages by Addie and Stefan to every backer. And these exchanges are even stored, and the early stage of the project is being carried into the future by Kickstarter's storage. Thus, by storing past transactions while at the same time providing contact to the present of the project this part of its history is publicised. Even after the campaign was over, many people entered the project via Kickstarter. Kickstarter has been a powerful 'socialiser' of the project. It is worth mentioning that I discovered the Lasersaur via Kickstarter as well. And so did my two other interviewees and participants in the project.

Kickstarter, however, was also an engine for the 'deterrioritorialisation' of the project, spreading the vision beyond Addie and Stefan and also taking control partly out of their hands. Giving potentially everyone the possibility to pledge money to the project and, thus, to have a stake in it could have been a strong destabiliser of the project's identity. With the project becoming a social project, Addie and Stefan were also deterritorialised, as they were now required to unfold the Lasersaur in cooperation with the group that was watching. This is what I meant above with the 'oh fuck' being a collective enunciation of the assemblage. Here we see how decentralisation was enabled by a centre. This centre collected different elements that contributed to forming shared desires which exerted pulls and pressures on the project's becoming. Such partly paradoxical interplays were important for the project's dynamics following its launch on Kickstarter: there are questions of openness and closedness, transparency and intransparency, accessibility and restriction, that cannot simply be seen one or the other way just because the Lasersaur is an open-source project. Rather, the project formed specific configurations of such tensions. In the following, I show how the assembled desire for the Lasersaur was turned into a technical object.

3.2.2 Prototyping the Lasersaur

With the successful Kickstarter campaign, what Addie and Stefan called the 'alpha stage' of the project continued. Addie and Stefan continued developing the prototype of the Lasersaur – they had already done some initial research before the campaign. As they pointed out in our interview, Kickstarter drew some very knowledgeable people into the project, who greatly supported the early development process with their knowledge about lasers and building machines. Furthermore, other open-source projects, e.g. on 3D printers and other CNC machines, provided much inspiration, suggestions and materials. Yet, during the first months of the project, it was mainly Addie and Stefan and loads of parts that they bought to experiment with and improve their initial design. They had a crucial function as collectors and assemblers of knowledge, as they mainly worked alone on the machine but could draw upon information that they found on the Internet. How was prototyping not simply a mode of development of a technical object, but of a collective machine that entwines an unfolding technical object with an unfolding form of social organisation? How was knowledge produced and circulated in the process of prototyping in which 'prototypes perform as working artefacts; artefacts whose significance is not given in advance, but is discovered through the unfolding activity of co-operative design-in-use' (Suchman et al., 2002, p. 172)? How does the prototype further develop by moving to other locations and organisations and what are the consequences of this for the project?

In November 2010, Addie and Stefan created a mailinglist and invited their supporters on it. The list was set up to store the emails and make them publicly readable. Writing on the list, however, was confined to registered project members. Due to their participation in other open-source projects Addie and Stefan knew a lot about the difficulties of online cooperation and interaction. There can be unfriendly emails, unstructured communication, negative or even overtly destructive attitudes. To help set a productive attitude amongst the community members, Addie and Stefan invited friends with experience in online collaboration onto the email list. As Stefan describes the problem: 'So it is really a lot of effort how you shape and make sure people are really nice to each other and like, you know, set the right tone' (Addie and Stefan, p. 19). Another design decision influenced the mailing list's atmosphere. Since the project's beginning, one can only actively participate in the online discussion as an initial backer on Kickstarter, or if one pays a small fee of $32. Reading the list, however, is free. This small amount of money is enough to only have interested people make the move into the email list – and it financially supports the work of Addie and Stefan a little. Since its launch, the mailing list has been the main element in the project to facilitate communication. It is a place where new people introduce themselves, and briefly a sense of 'community' is being acknowledged, such as when a member of FabLab Karlsruhe introduced himself and the upcoming building of a Lasersaur. One of the most active members of the list replied: 'Hi, welcome to the Lasersaur community. Answering questions (and asking a few of our own) is what we do best here – so don't hesitate to ask for help.' The questions that are being asked and answered, however, are mostly technical questions. The community is object-centred and aims to learn about and unfold the machine. The object is the medium that enables and engenders inter-subjective communication and communion, which is mostly about the unfolding of the object.

Eight months after the successful Kickstarter campaign, Addie and Stefan had the first prototype cutting with a 40W laser tube. A central step in the project, since from now on the prototype could be shared with the community. As Addie commented on this: 'The first time Stefan turned it on and ran it, remember this, like that cutting video [S: jaja], it actually worked and it was like oh wow this is crazy, like it actually kind of cuts! It didn't blow up or anything, so that was exciting' (Addie and Stefan, p. 4). The money they got through Kickstarter, however, did not last long enough to keep the research and development process going. To further improve their design, Addie and Stefan asked universities for support. A university's institute for digital interaction and digital media in the UK answered and supported Addie and Stefan in building the second ever Lasersaur together with students. Their residency there in May 2011 further improved the cutter and was the first test for the repeatability of the building process.

The second test for the repeatability took place when Tom at Piloten started building their Lasersaur in June 2011. The club had been conducting educational workshops about science and nature with children for several years. With their experimental and hands-on approach to scientific issues they want to give children an insight into science, sustainability and crafts that traditional schools usually do not offer. However, their workshops were getting more complex. In need of a (cheap) laser cutter to precisely produce materials out of paper, plastic and thin wood for workshops with kids, Tom started searching the Internet for possibilities and through Kickstarter was introduced to the Lasersaur project. Tom became a backer of the project after it was already successfully launched. In spring 2011, he received his 'Alpha Kit' with electronics and custom parts made by Addie and Stefan to build his Lasersaur along with standard industrial parts he still had to buy. A charity gave enough money (about €5,000) to fund the acquisition of the parts. And together with a class of pupils and their physics teacher, Tom built the third ever Lasersaur within two weeks. Since then, the Lasersaur at Piloten has been cutting materials for workshops, and it has become part of workshops as well. As Addie pointed out, Tom was not only inspiration as the first builder but also because he took the Lasersaur into a novel context of use. A creative movement that is normatively inscribed into the project: spread laser cutters into areas where they have not been used in this way before.

Although more Lasersaurs were started being build in summer 2011, and the knowledge base was building up, the project faced difficulties. In an email to the community, a year after the successful crowdfunding campaign, Stefan reports:

> 'We have spent the last year working pretty much full time on the Lasersaur while living and developing on just over 10k USD. It's been sort of insane. It's been a lot of late nights, long weekends and ramen. There is more to do. We love this project and our hearts are very much in the open-source movement, yet there are some realities which we face – like paying rent and buying RD materials which is becoming harder and harder' (https://groups.google.com/forum/#!searchin/lasersaur/future$20of$20lasersaur/lasersaur/PsJIGufwt0Y/SvECGnF5g5EJ, accessed 12.02.2014).

The email goes on with ideas about how to acquire more money for the sustained work on the project by Addie and Stefan – none of which were realised. Around the same time, however, Mark, director of Fabrik 2, introduced himself to the mailing list and soon became an important supporter of the project.

Fabrik 2 came into being with the new media enthusiasm in the 1990s. It conceives of itself as an interdisciplinary institute for design that provides an environment for research and education beyond the confines of the dominant cultures in universities. Accordingly, it has been aiming at experimental approaches to learning and design. Open-source projects such as Arduino micro-controllers and RepRap 3D printers (both of which started around five years before the Lasersaur) have been used in their work. At Fabrik 2 students and lecturers had already worked with a Chinese industrial laser cutter. However, Mark wanted to have Addie and Stefan share their experiences and expertise with the students, since he saw great potentials in this form of design work, especially for students and early career designers. He invited them to become fellows at Fabrik 2 and build a Lasersaur together with students. Addie and Stefan together with their small child moved into a flat provided by the institute and stayed for several weeks to build another Lasersaur. The work together with Fabrik 2 greatly improved the design of the machine and supported Addie and Stefan in making a living.

Besides the work of Addie and Stefan the community kept on growing. More people joined the mailing list and the discussion about the laser cutter. Whereas at first relatively few people contributed to the list, the numbers increased over the years. In May 2013, when I interviewed them, Addie and Stefan said that about 1,000 people were on the mailing list and about 20 to 30 very actively contributed to the further refinement of the Lasersaur. There has, however, also been a qualitative shift in the community. At the beginning the 'early adopters' were rather skilled in building machines. But with the documentation of the building process getting better and the project becoming more popular, people who were less technically skilled started to build a Lasersaur. This increased the amount of questions concerning the building process and the effort involved in moderating the mailing list. Addie and Stefan told me how this has become rather energy-consuming and annoying. And Tom and Mark pointed out how greatly they appreciated the patience and endurance especially of Stefan concerning the replies to the same questions over and over again, but by new people.

Although the project has already been running much longer than Addie and Stefan had initially planned, in spring 2013 they were satisfied that members of the community were increasingly modifying the design and taking over work for the project. Here, it is central that the laser cutter itself as an 'unfolding structure' (Knorr-Cetina, 1997) has its own pull in the project. People were demanding more precision, more speed, more strength of the machine, and some were offering parts of solutions. As Tom remarked, probably the project will never be finished – which he thought to be quite interesting from the perspective of an industrial designer, since in industrial design designs are finished at some point and then produced. Addie and Stefan when talking about challenges considered this unfolding character as well:

> S: 'there are a lot of technical challenges. It's like from making it work to making it work really well is you know all the work. We got it working in eight months after the Kickstarter it was working and then making it work so, you know, students at the university can just beat the crap out of it and it runs smoothly, it's so hard. That's like where all the work is.
>
> A: Even the commercial systems fail there. So then it's like finding ways to- [S: it's not just us] Yeah, it's not just us. I think that's the hardest part. [...]
>
> S: Sort of the last ten per cent are like two hundred per cent of the work. It's completely out of proportion and you kind of keep going because the community motivates you […] What kept you going in the beginning also makes you look at really complicated things that you never set out to solve' (Addie and Stefan, transcript, p. 24).

One of the surprises the technical object engendered was how much it offered and demanded for its continuation. At the beginning, Addie and Stefan thought they could release the project open source after six months in 2011. When they finally declared the project ‘mature’, it was the end of 2014. Yet, the Lasersaur has also helped them with their careers as artists and technologists.

A crucial feature of this second phase in the Lasersaur project is ‘prototyping’, which can be considered an increasingly important cultural form in the flux of contemporary technosocial arrangements (cf. Corsín Jiménez, 2014). This not only involved setting up a running machine but also organising a community based mainly on particular modifications of digitised interactions. Both, in a way, unfold, yet remain unfinished in a prototypical stage with no clear form being simply imposable on either. It is rather the recalcitrance of object and community, both open to change, that moves the machinic assemblage in unexpected ways. Although there is stability over time, it is provisional, established as a further feature of a prototype, yet never the last one. Prototyping takes place as a collective activity and is entwined with the shared desire for the machine. Whilst the above analysis proceeded along a chronological account of the Lasersaur project and the related activities of desiring and prototyping, I switch the mode of analysis below. Within the collective machine that centres on the Lasersaur there are complex relations and multiple and non-linear processes. To grasp these I analyse four different versions of the Lasersaur that do not neatly map onto each other yet are central to understanding the complexity of the project.

3.3 Manifold Lasersaurs

Central to open-source practices is the mobility of knowledge that enables the often distant collaborations in the projects between people spread across the globe. For people to collaborate in designing and using technical objects such as the Lasersaur, knowledge has to pass and circulate between and amongst them, be it ‘online’ or in co-present exchanges with people or objects. The relationships of space and knowledge are absolutely central to open-source practices. More explicitly than before I will consider the Lasersaur through the lens of the entwined mobilities of people, objects, information, data, images and texts (Urry, 2007; see for the ‘mobilities paradigm’ Sheller and Urry, 2006) which together produce open-source assemblages and the relations within them. These movements and spatialities are more complex than connections between different places. I analyse how the Lasersaur project simultaneously engenders and enacts different versions of its technical object, which correspond to different spatial configurations of it.

I do this based on the approach developed by John Law and others (Law and Singleton, 2005; Law and Mol, 2001; Mol and Law, 1994). This approach builds upon ANT in that it sees objects and knowledge as relational effects – think of Latour’s immutable mobiles that transport scientific facts beyond laboratories. But Law and others show how there are more versions of objects than the ones stabilised by actor-networks. They draw on topological reasoning and show how objects are the enactment of different relational spaces that go beyond Euclidean three-dimensional space. Space and objects turn multiple in this perspective. In the following I will analyse which aspect of the technical object Lasersaur is ‘taking place’ when and how. Law and Mol (2001) introduce four different enactments of objects that create their corresponding relational spatialities. There are objects in a region, network objects in network space, fluid objects in fluid space and fire objects in fire space. These different spatial enactments of objects, in some way or another, interfere with each other, yet they are distinct – they multiply ‘one object’ into different versions with different properties. Producing and dealing with such differences in the object is an important aspect of the collective machine of the Lasersaur project.

3.3.1 Places of Lasersaurs

First, I will consider the regions of Lasersaur and answer a seemingly simple question. Where are Lasersaurs? In April 2011 a member of the Lasersaur community set up an online map where builders of the

Lasersaur could simply add their location. By April 2014, 58 locations were put onto the map; two years later, 70 Lasersaur builds were mapped – far less than there are Lasersaurs, since not everyone put themselves onto the map. But with about 16,000 clicks in July 2016 the map shows that visibility is one important aspect to building a community: seeing Lasersaurs somewhere. This online map is one device to link the digital and material spaces that all host different aspects of Lasersaur. Furthermore, it gives a hint as to where the concentrations of Lasersaurs are: Europe and Northern America. One can find some other locations on the map, also in the global 'south'. But the picture is not surprising. The regions of the 'rich north' have the most highly technologised societies and are more conducive to such a rather expensive open-source project. Addie and Stefan told me how there are people in the community from all over the world. But as they and Tom pointed out, English, the working language of the project, also creates barriers, as would any language. This spatial division also roughly corresponds with the locations of FabLabs and similar spaces (see chapter on FabLabs) and indicates that open digital fabrication is concentrated in the 'rich north'. This shows how the project is based upon and performative of particular regional inclusions and exclusions that need to be taken into account against the claims that 'open-source' knowledge is for everyone and in 'the' public domain. Rather, also spatially a very particular public corresponds to the knowledge.

Besides the geographical space of Lasersaur the question of social space remains. Who are the people and organisations that joined in the project? This question is hard to answer. Addie, Stefan, Tom and Mark were all wondering about it. Of course, there are many people who introduced themselves and their motivations to build the machine. But there are many others who didn't. Addie and Stefan estimated that about 150 Lasersaurs were cutting around the globe in spring 2013. Addie said she once heard of a Lasersaur built by someone who never wrote anything on the mailing list. There is enough material and instructions online to do this. But the question can be answered at least in some detail. Besides hobbyists and individuals some small companies, e.g. design studios, built a Lasersaur to work with. Some schools built Lasersaurs to educate their pupils and to have the machine in their workshops. Similarly, quite a few universities had building projects. There are even examples, recounted by Addie and Stefan, where professors who were critical at the beginning, especially concerning safety issues, of the plan of Addie and Stefan built a Lasersaur with their students after they saw that it is doable. This strong link to educational and research institutions is shared by two of the largest open-source hardware projects so far. Arduino micro-controllers (www.arduino.cc) started based on a master's thesis at an Italian design school. The RepRap 3D printing project (www.reprap.org) – which was key to the recent 3D printing hype – started at the school of engineering at the university of Bath, UK. Going further back in time, even Linux has its early roots in the context of research and universities. A new form of education, research and technology-oriented organisation has also been important: FabLabs and makerspaces have been building their Lasersaurs and working with them, as FabLab Karlsruhe has been doing since autumn 2014. FabLabs centre around 'digital fabrication', i.e. 3D printing and so on, so a laser cutter is a neat fit. I just want to give a recent example. In January 2014, the makerspace 'Toronto Tool Library' held a public building workshop and has since been cutting with the machine. They have been proudly advertising their new machine on the Internet with a video that shows the machine cutting (http://vimeo.com/90188303, accessed 10.03.2014). These videos prove that building and using an open-source laser cutter actually works, and in the context of this discussion on the regions of Lasersaur they also prove that Lasersaurs exist at particular (material) places. In 2011, Addie and Stefan also sent such proof of the first cut around the world with a video of the first cutting prototype (http://vimeo.com/20809614, accessed 10.03.2014).

Apparent is the absence of industry or large companies in the project. Although this might change in the future, so far the Lasersaur has mainly been circulating in organisations and fields of practice that are more keen to experiment with open-source technologies than to produce things in order to sell them. Clearly, the Lasersaur project is not antagonistic to markets. Although the design has been under a restrictive Creative Commons licence that permits only non-commercial use of the design, Addie and Stefan have offered potential entrepreneurs to get in touch with them. In late 2013, in a further move towards fully releasing the project to the public, the two changed the licensing to allow commercial use of the design but restricted use of the Lasersaur name and logo, i.e. the ‘branding’ of the project, to only non-commercial use. At the time of writing, however, there has been no attempt to build a business around the Lasersaur or its design. During the past years, however, companies have emerged that particularly address ‘makers’ and also sometimes offer machines that have an open-source design. For example the company FabCreator (www.fabcreator.com, accessed 20 July 2016) (notice the reference to FabLabs etc.) started to offer three laser cutters, with the smallest one (much smaller than the Lasersaur) being open source. Lasersaur can actually be considered a project that helped that market to emerge.

3.3.2 Network of Lasersaurs

To make the Lasersaur design moveable and its building repeatable and to give it the regional distribution analysed above the design needs to be stabilised, and different sites ‘online’ and ‘offline’ need to be connected in a reliable manner. There has been much work to build and sustain relations that enable the design and knowledge to be held stable in network spatiality – the form of existence that the classic ANT studies focused on. This is more than regional space, since ‘any given interaction seems to overflow with elements which are already in the situation coming from some other time, some other place, and generated by some other agency’ (Latour, 2005, p. 166, italics in original). Tracing these overflowing relations traces the network that makes the Lasersaur an immutable mobile.

A central element in the Lasersaur assemblage is the ‘manual’ (http://www.lasersaur.com/manual/, accessed 11.04.2014). The manual is not one document. Rather it is the umbrella term for the different forms of information about building the Lasersaur that Addie and Stefan assembled on the project’s web site for anyone to read. By now, the manual is an impressive extensive document of the production and circulation of knowledge that has been taking place in the Lasersaur project. But this took time to develop. When the prototype was cutting, the manual was rather rudimentary. It was enriched through the further design work of Addie and Stefan and the feedback they got on building the machine from others. When certain design changes were effectively tested by the two or other members of the community, Addie and Stefan further worked them into the manual, which was revised and updated many times. A lot of work transforming (email) conversations, experiences with building and experimenting with documenting a building process into a well structured manual has been made durable and accessible online.

Crucial for the transformations of the manual, Addie and Stefan said in our interview, has been the social character of the project. When they built the second Lasersaur together with students at a design institute, they learned a great deal about how other people approach the building process and encounter difficulties. In a similar way, later on, builders gave ‘feedback’ based on questions via email about building the machine and one could include answers in the manual. When the heterogeneity of the community increased with more less technically skilled people joining, the demands on the manual increased as well. Addie and Stefan wanted the Lasersaur to be repeatable as easily as possible, but ‘opening up’ knowledge to a diverse public required learning and effort and a manual with more details. For this learning the mobility of Addie and Stefan has been crucial for the Lasersaur project. In 2011, they worked at two different design institutes. They presented the Lasersaur at a maker faire in the US, a popular event in the ‘maker movement’, and even won an award. They were invited by universities and FabLabs (or hackerspaces) to give talks. Each of these helped to better understand relations between the laser cutter and its public.

Tom, who already had experience with mechanical technology, built the third Lasersaur with pupils. Two aspects of the then rather limited manual helped him a great deal in building: a CAD model, a digital technical drawing, Stefan had created along with the prototype, and 88 photographs that were taken during the assembly of the second machine and put online. These provided much of the information for putting the hundreds of standardised industrial parts he had bought for several thousand Euros together into a working laser cutter.

Ambient machine: CNC and CAD – from design to sharing

The drawings in figure 2 below are from the Lasersaur manual. Since the end of 2014 they can be viewed in any Internet browser. Before that the way to see these technical drawings was in CAD software programs, of which there already existed open-source versions. From the first Lasersaur version onwards, the CAD model included all parts and their relation to each other. Zooming and rotation of the graphic allow builders to see in detail how the parts need to be assembled and what the measurements of the machine are. In our build at FabLab Karlsruhe the CAD graphic was the most important information that guided the actual building process.

Software and its configuration in digital technosocial arrangements is crucial for open-source hardware. On the one hand, these CAD graphics show how it is possible to move explicit knowledge in software very stably through the Internet and how this knowledge can be enriched with new features in a CAD program rather easily. On the other hand, CNC (computer numerically controlled) machines are fed with and controlled by software. A simple graphics program and the Lasersaur firmware are enough to turn a two-dimensional drawing into a command to laser something. The question whether software is 'free' or at least widely accessible as championed by the free software and open-source software advocates is, therefore, still of huge relevance for open-source hardware.

Besides designing and controlling machines, software is a key ingredient in novel technosocial arrangements that are central to digital fabrication and open-source hardware. People started to upload these designs of objects that CNC machines can produce to online platforms – the most popular so far is Thingiverse, part of MakerBot Industries, which began as an open-source 3D printing company but shifted to closed source and no longer made its designs public after it was bought by a large investment firm (www.thingiverse.com, accessed 12.04.2014). The mainly free design files, most of which are for 3D printers, but there are many for laser cutters, can be downloaded and modified and sent as instructions for the manufacturing process to the machine. This is one reason why Addie and Stefan consider the Lasersaur to be an infrastructural project, based on which many other projects can grow. The technosocial arrangements of open-source hardware are, in a way, themselves a computer-aided design.

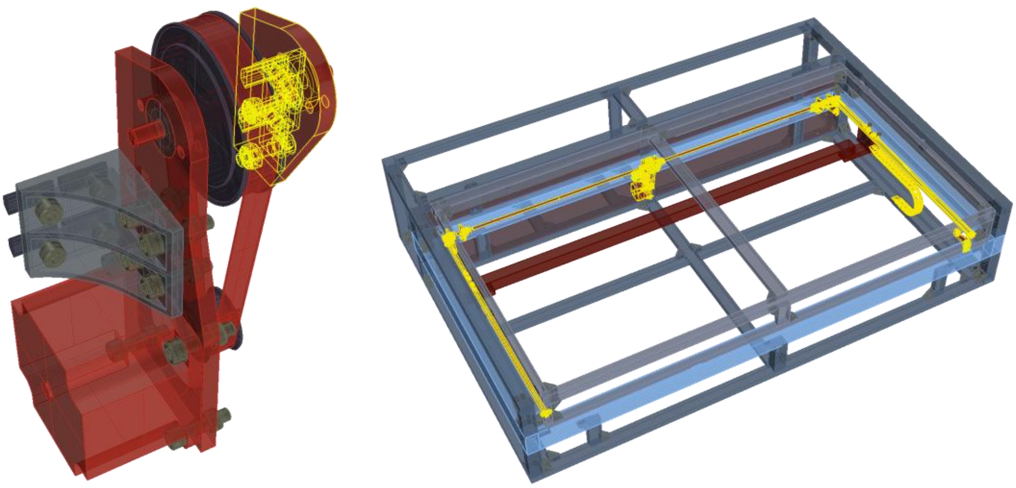

Figure 3.1: Lasersaur CAD drawings, https://github.com/nortd/lasersaur/wiki, accessed 11.06.2015

Further central information for building the laser cutter was provided by the parts of which it was made. For Addie and Stefan a lot of the development process involved finding suitable parts for the machine and uncomplicated design solutions that were easy to realise. These tasks were strongly supported by other open-source hardware projects where certain mechanical parts and configurations had already been tested and suppliers suggested and these suggestions were available online – forums and mailing lists, again, are crucial here as in the Lasersaur itself. Therefore, a central part of the manual is the 'bill of materials', which lists all the parts needed – from screws to laser tube – to build a Lasersaur, and this document even suggests suppliers with whom Addie and Stefan have had good experiences. Producing the bill of materials has been such an important task for Addie and Stefan that they even started an open-source software project based on their experiences to facilitate this process (http://www.bomfu.com/, accessed 17.04.2014). In an interview the two said that they see the bill of materials as the centrepiece that differentiates open-source software and hardware projects, since it establishes the necessary link between the open-source design and the materials (http://eyebeam.org/press/media/videos/openart-fellows-nordt-labs-discuss-their-project-bomfu, accessed 17.04.2014). The bill of materials even exists in a US and an EU version, since different vendors for such parts are operating there. If one tries to order from other vendors, as was the case in the build in FabLab Karlsruhe with the aim to save money, the Internet is crucial for finding sources for sometimes specialised parts. A small group of members invested dozens of hours to find suppliers and used parts already in someone's or the FabLab's ownership and we saved approximately €2,000 in comparison to the suggested vendors in the manual. This shows, however, how the Lasersaur depends on industrially mass-produced objects and their capitalist geography of worldwide shipping and movement. Finding these commodities and bringing them together is crucial for building open-source hardware objects. These about 1,000 standardised parts form the robust and mainly cheap building blocks for the machine. However, for finding, identifying and arranging the technical parts of the Lasersaur, other entities are important as well: the Internet itself, digital cameras to produce images, measuring and other standards, and so on. Bringing these all together in a network is an enormous task. As Addie said: 'if you're working with multiple countries getting something in the US is different than getting it here [...] and then there's metric versus [imperial], so all these different ways of measuring and that stuff these little things are very like hard to translate internationally' (Addie and Stefan, transcript, p. 3).

The Lasersaur is also based on many 'pieces' of other open-source projects (in technical and conceptual ways). The electronics and software of Lasersaur are based upon open-source projects which provided much conceptual inspiration. To acknowledge this, the Lasersaur website states: 'Mad props to reprap.org, www.cnczone.com, arduino.cc, grbl, buildlog.org, and their giants' shoulders.' (www.lasersaur.com, accessed 24.04.2014). There is much learning from each other and mutual observation of other open-source projects. Drawing upon parts of the Lasersaur design, a very small open-source laser cutter was already created (http://www.smartdiys.com/smart-laser-mini/, accessed 04.02.2015). A fully open-source version of a machine like the Lasersaur with all parts being designed and built in an open-source approach is still a thing for the future. Fully open source, however, is the software operating the Lasersaur, the 'LasaurApp' (https://github.com/stefanix/LasaurApp, accessed 12.04.2014). This is the interface between PC and laser cutter and steers the motors and the laser beam to cut what is shown graphically on the PC. Addie and Stefan used software of the RepRap open-source 3D printing project, which was steering 3D printers, as the foundation for their app. The software is based on Linux and, therefore, is the most direct link to the early days of the open-source culture. Similar to other design decisions, Addie and Stefan took the easiest version of this software to make it more accessible to people who are not that skilled with modifying software. The LasaurApp is accessible from an Internet browser on any PC as long as there is a network connection to the Lasersaur set up. It was another design decision to make the interface to the machine flexibly accessible. Furthermore, the LasaurApp instructs the machine to cut based on 'scalable vector graphics', an open standard for digital graphics for which open-source software programs exist to create and modify drawings. On the software layer of the Lasersaur we find a mode of connecting that is almost entirely based on open-source objects. These, as well as all the other objects, have to be considered as parts of the network of the Lasersaur that stabilises and reliably moves it.

The Lasersaur manual is characteristic of many aspects of the Lasersaur and other open-source projects, as it constitutes a central node in the network. The manual gives safety warnings, describes the building process, gives advice for operation and maintenance of the machine and explains how to get help or inspiration, e.g. on the mailing list. Due to these manifold aspects of documentation that have been building up, the manual aims to cover almost all aspects of technical reality, to recall Simondon once more. Whereas ‘user manuals’ or ‘operating manuals’ for industrial objects may also be rather advanced, they typically cover information on how to use finished objects, and not about building or maintaining or even changing them. A member of the FabLab made a striking comparison between Lego and the Lasersaur. In both you assemble standardised parts with the help of a detailed description. Whilst play is still important in the Lasersaur, in important ways it differs from Lego. In Lego the building manual comes prefabricated; in the Lasersaur it had to be produced in a process with an increasing number of people building the machine. Furthermore, to establish the network in which the manual is a central node the practice of searching for parts and information beyond what the manual suggests is a crucial activity. Yet Lego and Lasersaur both exemplify how explicit technical knowledge is stabilised in the relationship between representations and technical objects. In the next section I consider why this makes the Lasersaur also a ‘soft’ and changing fluid object.

3.3.3 Transformations of Lasersaurs

While stability is important for reproducing the Lasersaur, the project has also created considerable transformations of the object. In this section I focus on the movements and slight transformations that have been part of the object and these do not only entail technical aspects. To capture such ongoing transformations, Law and others speak of fluid objects which do not have the rigid control of networks that hold objects in a certain shape. Fluid objects are rather like fluids that flow. They hold together, yet they constantly change as they move along and flow around other entities or mix with other fluids. Fluid objects paradoxically stay the same because they slightly change – they are ‘mutable mobiles’. Law and Mol (2001) took this argument from an ethnographic study of a water pump in Zimbabwe that spread into many villages, yet never was exactly the same. Its public design (almost a kind of an open-source hardware water pump) allowed for all kinds of changes in the object and in its social relations (Laet and Mol, 2000). More explicitly than in regional and network space, time plays a crucial role to configure fluid objects and their flows. How does Lasersaur flow?

Considering the technical side of Lasersaur, the machine is designed to allow for changes in many ways. The modular design makes it possible to depart with many parts from the bill of materials and modify the laser cutter. For example, there exist 100W, 40W and 150W versions of the Lasersaur with different cutting strengths. A French art school simply built a drawing machine by replacing the laser with a pen (http://numerique-tendance.tv5monde.com/152_projet_voir---ecran---voir, accessed 13.03.2013). It’s also relatively easy to change the size of the machine. Such changes, however, can sometimes lead to problems and cause extra work for the community. Stefan recounted how the change of the cooling system for the laser by one member of the community caused a failure in the machine that was extremely hard to track down since, at first, no one thought of the ‘non-standard’ cooling system. Yet such technological modifications or ‘derivatives’ of the design are encouraged by the discoursive coding of the Lasersaur assemblage. And Addie and Stefan reported that they were happy that such modifications had been increasingly taking place since the start of the third year of the project. As the introduction to the manual says, ‘an open source design can improve over time through the collaboration of many people. We hope in three years it will have evolved to the point where it has multiple robotic arms sticking out capable of building space stations :)’ (http://www.lasersaur.com/manual/, accessed 15.04.2013). Although partly a joke, this links to the hacking culture which recognises and highly values creative modifications of technology (e.g. Coleman, 2012).

Ambient machine: open-source licensing

Important in making open-source hardware objects flow are legal licences that help to avoid certain effects of copyright and patents, both known to suppress the change of objects. From the early days of free software onwards, the legal aspects of open source have been a crucial issue for activists and researchers. This often led many to see open-source practices mainly as a critique of intellectual property (Coleman, 2012; Berry, 2008; Kelty, 2008). Nowadays there is a huge variety of licences that keep immaterial objects (software, images etc.) public in a legal sense. One of the most successful projects here is Creative Commons, a US-based non-profit organisation that has been working on legal licences that support the free and continuing public sharing of cultural works and to protect them from unwanted privatisations (Linksvayer, 2012). Lasersaur uses these licences for the manual. The normative and discursive links and the licensing, which provides a certain fit to national legal regimes, could travel into the Lasersaur assemblage via logos of and references to Creative Commons licences which are available online. The image sorts the possibilities for licensing that are offered by Creative Commons. The attribution to different degrees of 'openness' condenses years of debate about licensing and open source.

There are still only a few open-source licences that explicitly address hardware and the different legal issues when it comes to intellectual property and material objects. The first open-source hardware licence is considered to be the TAPR OHL (Tuscon Amateur Packet Radio Open Hardware Licence), which was released in 2007. Interestingly, radio amateurs were an important predecessor to open-source enthusiasts as they have been building their own radios and exchanged knowledge about them by using the radios. This started already after the First World War. It is, however, the massive spread of open-source hardware objects that engenders much discussion and certain projects that aim at producing novel licences or to establish best practices of licence use (https://en.wikipedia.org/wiki/Open-source_hardware, accessed 20.01.2015). Open-source licensing and discourse about it certainly is an important aspect in the global open-source assemblage that challenges the seeming naturalness of intellectual property, which is a political-economic and legal construct. This study aims to show, to make something open source, legal arrangements are not enough. Rather, open-source knowledge has to be practically produced and circulated on many dimensions.

Such modification of technology, however, from the beginning aimed also to be the modification of the social uses of technology in the Lasersaur project. The goal to have a comparably cheap laser cutter was also the goal to get it into the hands of people who wanted one but couldn't afford it. The normative production of the public open-source design aimed to produce the normative public spreading of the machine itself and add indeterminacy to laser cutting technology: it should become experimentally appropriated through uses other than industrial ones. When Tom was building his Lasersaur with school children, Addie said, that was what they wanted. For Mark at Fabrik 2, the Lasersaur was an important educational project for his students to show them the possibilities for their own future work.

At Fabrik 2, as I indicated above, there is another industrial laser cutter, which the students have been used to working with. In comparison to it, the Lasersaur is not used that regularly. The industrial laser is better integrated into the everyday routines and the network of objects that co-constitute them. As Mark said:

> '[The Lasersaur is] a different tool really, that's exciting […] it's a beautiful object, but it never really was accepted by the students. Uhm, it demands a different understanding. There is this dogmatic open-source mentality, such that now you should change everything to svg format [an open-source standard for digital graphics] instead of using Illustrator [software by big US company Adobe], what every reasonable human does. […] It's somehow sectarian, and that's also the allure, you feel part of a movement. […] It's reasonable with the general argument to not be dependent upon [big companies], but if you want to simply laser some

> paper in your everyday work it's inconvenient. […] Yet, once in a while there are such freaks like the student who just finished who developed this [modification for Lasersaur to cut bamboo]. He worked on this really cleverly and handed it over to the [Lasersaur] community. And he was really happy to work with such an open-source thing, and he believes in it […] I think that was a good experience' (Mark, transcript, pp. 5, 6, 7).

In some cases the Lasersaur might deliver a less easy-to-use experience, yet to frame it simply as an object to be used does not really get at what the Lasersaur is; this is what Mark hints at. Being part of the 'sectarian movement' means trying to change the objects that co-constitute everyday life, be it in terms of using open-source software or creating add-ons for the Lasersaur. Knowing such unfolding objects like the Lasersaur involves, as Knorr-Cetina puts it, 'a sense of bondedness or unity (an identity feeling) with objects, a moral sense (the oughtness of approaching them in certain ways), and states of excitement reaffirming the bondedness' (Knorr-Cetina, 1997, p. 20). Similar to Mark, Addie and Stefan and Tom were wondering in the interviews how to meaningfully frame the Lasersaur. Addie and Stefan saw the Lasersaur at the beginning as a tool that they wanted until they found out that it is much more. They said that, ironically, other people use it as a tool much more than they do, since their task had become the ongoing support of the transformations of the project. Tom wondered whether other people actually wanted to make the Lasersaur a perfectly working tool for everyday work or if they wanted to modify it in different ways. He contended that one needs a special understanding to take on open-source objects and was sceptical whether most members of the project actually wanted to simply use the machine.

As the Lasersaur flows into and along people's lives, it also starts flowing beyond established routines and meanings. And the Lasersaur's flow pushes the people who respond to it also partly outside the routines and meanings they have established with and for other objects. In short, flowing with the Lasersaur transforms the people as well. Much more than simply using this machine, engaging with the Lasersaur project is a process of learning, i.e. a process of change. Building a Lasersaur is becoming with the growth of the artefact, what Ingold calls correspondence. Accordingly, in the correspondence with the flows of the machinic assemblage of Lasersaur people grow into knowledge (cf. Ingold, 2013, p. 13).

The knowledge that flows in between Lasersaur and people is not simply technical knowledge and social skill; it also grows imaginations and hopes. At Fabrik 2 they were already working with other open-source projects before they took on a Lasersaur. Yet, for Mark, the Lasersaur was an inspiring demonstration of what is actually possible with open source and the real-time cooperation mechanisms upon which it is built. Of course, the flows of Lasersaur were only some of the flows with which Mark moved along, but since 2013 a Lasersaur has been standing inside of Fabrik 2's largest recent project with the aim of transforming an old factory building in a stricken industrial region into a centre for creative work and fabrication. They have chosen open source to be one of their guiding principles and Mark stressed that this seems to be the crucial task now to use collaborative openness as a way to organise such spaces. It is also in such ways that a fluid Lasersaur corresponds with environments that are themselves changing.

As more open-source projects and objects have been emerging, people have increasingly started to imagine whole networks of open source, which in their imaginations could in the near future co-constitute much of social life. In 2011, for example, the project 'open-source Ecology' included the Lasersaur in their set of machines with which they want to create an 'open-source civilisation'. The project has been building prototypes of machines for modern farming since 2003, and in 2006 started the 'Global Village Construction Set'. A 'set of the 50 most important machines that it takes for modern life to exist [...] a modular, scalable platform for documenting and developing open source, libre hardware – including blueprints for both physical artifacts and for related open enterprises' (www.opensourceecology.org/about-overview/, accessed 04.04.2014). Open-source Ecology is clearly the most 'utopian' project in the recent open-source scene that I have come across. It has strong similarities to the technovisionary communes of the US counterculture in the 1960s and 1970s (cf. Turner, 2006). Yet it has also become one of the most prominent open-source projects; it has received a lot of funding and donations as well as attention in the media – even Noam Chomsky has noticed it. The set of machines that the project is promoting are intended to be able to build other machines – and the Lasersaur is seen to contribute to this. Addie and Stefan were strongly inspired by the modular approach to building a whole system of things and machines – they also see the Lasersaur as an infrastructure, an enabling platform for other open-source hardware. In November 2013, the founder of open-source Ecology worked at Addie and Stefan's studio in Innsbruck to build a Lasersaur. Besides building they experimented with novel forms of documentation of the building process, i.e. filming each step of the assembly and sharing materials with novel online platforms (www.opensourceecology.org/ose-lasersaur-build-documentation-sprint/, accessed 04.04.2014). Together they produced a transformed version of the manual, which also has to be considered a flowing object.

Flowing transformations of technical objects, practices and imaginations are another version of the Lasersaur. However, besides such continuous flows of the object and its environments, there are ruptures and jumps that discontinuously change the Lasersaur and turn it into another kind of object. In the next part I turn to these.

3.3.4 Disjunctures of Lasersaurs

Such smooth flows are but one form of transformation that can be found in the Lasersaur. Another form of transformation that is more intermittent can be identified. Law and others elaborated fire objects to take into account the discontinuous which is not present in the other types. One has to

> 'think of them [fire objects] as sets of present dynamics generated in, and generative of, realities that are necessarily absent. […] Such objects are transformative, but the transformations [...] take the form of jumps and discontinuities. In this way of thinking, constant objects are energetic, entities or processes that juxtapose, distinguish, make and transform absences and presences. They are made in disjunction. Fire objects, then, depend upon otherness, and that otherness is generative' (Law and Singleton, 2005, pp. 343–344).

Important to understand fire objects is to not simply see multiplicity and otherness as an effect of different interpretations. Fire objects are multiple in the absences and presences that they co-constitute; they are plural, messy objects. What are such presences and absences of the Lasersaur?

There is a certain structure in the machinic assemblage itself that withdraws elements from other elements. Each Lasersaur is based upon the work of many people, who are not present at the site of a specific machine. While there are interactions and communications with other people, everyone I interviewed did not know who most of the other people were that contributed to the Lasersaur, why they do this and how they use their machine. Despite the rhetoric of openness, much remains opaque. Otherness, the other, is, therefore, often present as an absence. However, it is integrated via the plurality (e.g. in versions and forms of use) of the technical object being the smallest common denominator between those who remain other to each other. Here, however, in the co-constitution of indeterminate technical object and sociality lies a key normative aspect of the project. When asked what they understand as open source, Stefan answered:

> 'It's a way of collaborating, and what's very important about it, you know, it sets up a set of expectations. [...] What happens when you collaborate what happens when you, you know, put your work in, and how can you proceed? So the expectation is that it stays in the public domain, and this allows a different collaboration model, a different way of collaborating than if you don't have these expectations.'

Addie added:

> 'open source is kind of this idea, it's a way of working, I don't know whether it's necessarily a tangible thing, it's kind of like how do you define art, or how do you define happiness, it's there, it's a grey area, and there is not the fine line of what is right and what is wrong with open source. For me, it's this idea that you collaborate and release your ideas freely so that other people can share them' (Addie and Stefan, transcript p. 1).

In releasing their vision for the technical object into the public domain, Addie and Stefan took a first step to give away control over their idea and to build the expectation that this is OK to do for others as well. This is an invitation for others to co-determine the further unfolding of the technical object without knowing everything. Thus, trust is an important aspect that enables collaboration with a fire object that inherently entails non-knowledge. This includes accepting what others might do or not do with the technical object and accepting that one does not know. Coleman, who argues that liberalism is central to free and open-source software, showed how normally 'big politics', e.g. the aim to build an alternative to capitalism, is absent in these projects. The politics centre around 'free' software, a public technical object that is to be produced and further unfolded. Therefore, this object can participate in many different contexts of meaning (Coleman, 2012, chapt. 4 and 5). The Lasersaur project does not only entail openness towards unknown others, it is in turn also the absence of others, which is generative of the presence of a plural (fire) object.

Crucial for this technical object is that from the beginning of the project industrial laser cutters were present because they were absent. Addie and Stefan wanted to develop an affordable laser cutter that could move into contexts where industrial lasers would not. Furthermore, the machine is partly made of parts that are used in industrial lasers, yet in the Lasersaur they assemble into something else. And this something else is made through relations that actively depart from the relations that an industrial laser cutter would engender. The Lasersaur's significance lies in the othering it produces concerning the dominant relations between people, knowledge and objects. The presence of the Lasersaur makes some aspects of these relations absent. But these also make the Lasersaur partly absent, e.g. prevent it spreading even further across the globe. In a way, the presence of each one relies on the absence of the other. This, however, is not a simple either or alternative. It is a process of making present and making absent, of producing otherness.

This is especially the case since a laser cutter is complex and potentially dangerous. Before, during and after the actual building of a Lasersaur, safety was a prime issue in FabLab Karlsruhe. Even the reflections of a 100W laser beam could easily blind people or harm them otherwise and the electric current could create lethal electric shocks. Although there are many safety measurements in the Lasersaur design, it is still a question of applying them properly in the process. And since the Lasersaur was to be used in a public workshop, some people in the FabLab were extra cautious to make sure that the machine was built and operated safely and in accordance to certain industrial safety standards. Addie and Stefan also encountered much criticism at the beginning which centred on open sourcing such a dangerous machine. They emphasised, however, that actually building a Lasersaur helps people to operate it properly. Thus, while I could not find any reports about serious accidents with the Lasersaur, its dangerous side is present when people approach this object. In a way, the Lasersaur's fire in a literal sense is latently present and part of the object, although much effort is being made to keep it absent.

While accidents are a probable possibility of Lasersaur, it also engenders other possible futures, futures that might imply larger technosocial change. Stefan gave a hint how his hopes, inspired by the Lasersaur, were sometimes similar to fire:

> 'We talk a lot about how powerful personal fabrication is and the Lasersaur being one of those canonical machines for personal fabrication. How much does it enable people to do things and invent new things and we kind of go back and forth. It's like, oh, you know,

> everything is gonna be invented in this way and locally produced, and at other times it's like, oh, some things are so complex you can't possibly, like, cultivate that knowledge locally. If you really look into industrial processes, some of them are so advanced that it's hard to imagine how you bring them to local production. [...] I really go back and forth between, like, this is totally possible [...] it's sort of this paradigm change that happens. And sometimes I feel like, uh woah, this is never – how do you manage this? How, you know; you need like a dedicated group of people and that's all they do' (Addie and Stefan, transcript, p. 28).

In being already different to the dominant ways in which technology is being produced and used, the Lasersaur hints at a potential shift, an imagined possibility of large-scale social change, the 'paradigm change' that Stefan talks about. Although such a shift is absent, its prototypical, experimental, hypothetical forms are noticeable in machinic assemblages like the Lasersaur. And with ambivalent experiences being made, hope for this shift is present/absent. As a fire the Lasersaur is generative of transformations, challenges, difficulties, opportunities, novel skills, or more generally of novelties that embody significant differences to what is dominantly present. There is a potential for othering, for making different, that the Lasersaur offers – partly visible, partly concealed. In its fire way of being the Lasersaur assemblage hints at a 'real future' (cf. Bloch, 1995), one which departs from a simple prolongation of the present, but one not yet completely born. This sense that some jump in history, some paradigm shift, might be latently under way is probably the most important aspect of the Lasersaur as fire object.

3.4 The TechKnowledgy of open digital fabrication and its objects

To sum up the analysis of the Lasersaur I recall an instance where much of the TechKnowledgy of open digital fabrication in relation to technical objects was visible. It was the start of the active building process of the Lasersaur in FabLab Karlsruhe at the end of 2014. In this brief ethnographic account, characteristic interruptions of flows of different elements are visible of how the TechKnowledgy is taking place in the realisation of a collective machine.

When it was eventually strongly enough desired and decided that the FabLab would build a Lasersaur, a group was set up that would organise the building process. A first task was to get the necessary parts. Three people engaged with the bill of materials of the Lasersaur project and looked up possible suppliers, drawing almost every register of contemporary online shopping, actively navigating through the digitised technoecology and linking the explicit knowledge of the project to markets for materials. The aim was to save money on the parts. Some parts were donated by people involved in the FabLab and when weeks later the shipments arrived, it was a huge effort to keep track of the around 1,000 individual pieces that were the building blocks for the machine. The people in charge, however, were already experienced in shopping, identifying and handling such technical parts. Such knowledge was central when a group started the building process of the Lasersaur with aluminium extrusions and screws that were to constitute the frame of the machine. This is the first step in the Lasersaur manual, which guided the creation of a network object in the room. A central task, however, was to make the manual correspond with the materials and people. And although the photographs, texts and technical drawings of the project were very precise, it was very helpful to have people in the room who had tacit knowledge on how to identify the correspondence of technical drawing and material parts and knowledge on how to assemble pieces together. While many parts are highly standardised, the additional hints by people, for example on how to most easily connect or disentangle two pieces of metal, proved crucial for the group to work collaboratively on the object. And these were not part of the manual. Such practical knowledge on how to do particular tasks was also important in operating the complicated software that displayed the technical drawings – sometimes one had to zoom in or to change the angle of view to more clearly understand the design. However, after two or three hours everyone in the group understood how to make the explicit knowledge of the manual, the pieces and the practical assembly correspond; people had acquired new tacit knowledge. Several other evenings followed with similar processes repeating: different aspects of the machine's assembly demanded different skills and forms of engagement.

Roughly three weeks after the start of the building process the Lasersaur was cutting for the first time. It was a moment of great excitement, and the group was proud that they managed to build the machine. Yet, although the machine was cutting, it was far from being considered finished. The Lasersaur revealed flaws in its operation, e.g. imprecise cuts. Also, during the building process some people discovered aspects of the design that they did not like and wanted to improve, e.g. in the electronics. Furthermore, the Lasersaur still was not well integrated into the room of the FabLab; a dedicated table and an air filter was planned – which later became a significant contribution to the Lasersaur project by FabLab Karlsruhe. The latter is necessary to prevent possible poisonous gases from flowing into the room while cutting particular materials. Local conditions are important in many ways to support the assembly of the machine. One has to have the money, the basic skills, the tools, the social support, the space and time to assemble a Lasersaur and to assemble the local conditions with the Lasersaur. Therefore, although our reproduction of a Lasersaur was in the room and working, there were still many tasks that the group wanted to take on. The machine in the room was a local prototype and a fluid object.

I want to call this the building and learning paradox of open-source hardware, which is based on a particular relationship of explicit and tacit knowledge. Whilst there might be much explicit knowledge available and proof that others have used this to build machines, explicit knowledge alone does not build machines. People have to do it at particular places. And they can make use of explicit knowledge only through actually engaging with it and with materials; a process in which they build upon and unfold tacit knowledge. Only through actually building, for example, a Lasersaur do you really know how to do it, and you learn about the machine itself. Many improvements to the design that the Karlsruhe group wanted to make came into being through the actual involvements of the people with their hands, eyes and bodies with the material machine. However, in most cases such 'deficits' were discovered after the documented version was realised. Changing it required disassembling parts, buying different parts in some cases and constructing differently – in the case of a laser cutter this can be rather expensive and time-consuming. Partly due to the time needed, only some of these changes were shared in the Lasersaur project. The Lasersaur as fire object was, therefore, absent as a properly working machine until the demanding process of building it was over and came into existence as a working machine with people able to use it.

I have shown how the various objects in the Lasersaur project enable and afford particular involvements that are in significant ways different to the affordances of industrially produced laser cutters. But I have also shown how involvement with the Lasersaur is demanding and configures a particular public that is able and willing to engage with this machine and its 'open knowledge', which is not open to everyone. Put differently, the Lasersaur is 'open' to those who put the work and the resources into corresponding with the project, provided they are able to do so. Open knowledge has to grow into people, and they have to grow into it (cf. Ingold, 2013). From my own experience as part of this group I can say, however, that such effort in participating in the Lasersaur network can pay off. Although I was not an expert in building machines, by now I would consider myself able to build and repair most mechanical aspects – the subtask I was involved in – of the Lasersaur, since the correspondence with the object changed me. Could I have built a Lasersaur myself? I am not sure, but I cannot rule it out either. It would have taken much more time, more money and more failures to endure. I would have needed to learn many different skills and to more actively engage with explicit knowledge online, to get tips from others and to learn from the objects. Others have done this. Addie and Stefan, for example, were not experts on laser cutting, but years of work on the object and the project turned them into ones. This relationship of 'open' explicit knowledge, resource requirements of material technical objects and the time needed to work on technical objects point towards important constraints of 'open-source hardware economies'. It shows that this is not a 'for free' economy, although much explicit knowledge might be freely and publicly available. Considerable organisational effort and resources have to be put into enabling and sustaining work on these projects and to produce the knowledge in the first place. The idea behind a project like the Lasersaur, however, is that the collaboratively created explicit knowledge hugely reduces the work and time needed to reproduce a Lasersaur.

This chapter has shown and analysed how recent technosocial changes in the characteristics of technoecologies and in organisational forms and cultures have made projects like the Lasersaur possible. In particular open objects with more possibilities to be connected to other objects and changed have been fostered through digitised technoecologies. Procedures such as mailing lists, crowdfunding platforms or the sharing of technical drawings in online repositories depend on malleable and indeterminate open objects that serve as an enabler of these. These objects and their wide distribution across technologised societies have been central in imaginatively and practically fostering open-source hardware projects that connect the circulations of digital objects to material objects. In addition to the particular digital circulations and organisational forms that are enabled and unfolding in these technoecologies, industrial objects and materials have become accessible for individuals, often cheaply through globalised forms of trade and commerce which also build upon 'online' coordination. Projects like the Lasersaur develop designs for machines and produce explicit knowledge that corresponds with the project's public, digital and material objects. I analysed the complexities of producing, circulating, stabilising and transforming such relations, a collective activity which was product and producer of a particular TechKnowledgy that transcends the Lasersaur project, yet was configured into a particular collective machine in this. In fact, the Lasersaur manual with its step-by-step instructions is an explicit representation of a building procedure that was collectively developed in a process that drew upon other procedures to enable the online collaboration of a group.

From the example of the Lasersaur a particular form of modularity can be condensed that is an important characteristic in the TechKnowledgy of open digital fabrication. Simondon (2012, 2016) argued that technical objects are the foundation of technology and analysed how technical creativity is based upon the combination of existing objects, out of which novelty can emerge[7]. Technical objects are part of human history because they 'store' past knowledge and work and make it available in a condensed form and throughout history they have been combined in increasingly complex ways to constitute technoecologies. Technical innovation is the combination of existing objects into novel technical objects, a process that also depends upon the constitution of technoecologies. Following this theory, technology, considered as a process, is based upon modularity. Modularity precedes technical creativity, which, if successful, increases modularity. Seen from this perspective, a technically highly creative society is able to draw upon many technical modules and fosters and enables their combination.

If every technology is modular, however, what is special about open-source hardware projects? The Lasersaur and similar projects aim to organise modularity and the technical modules themselves in a different way than other TechKnowledgies do. It must not be forgotten that people actively combine technical modules. They do so, however, within societies where particular ways to access and to know about technical objects as modules for technical creativity exist, which enable and constrain different forms of combining modules. In open-source hardware the aim is to produce and to digitally publicise explicit knowledge. This is a process that can directly produce technical objects, such as software objects. But in open-source hardware it mainly produces knowledge to facilitate the correspondence with material technical objects. The Lasersaur manual is in this sense especially a repository that encourages and informs about how to orient in, make use of and transform contemporary technoecologies. One can see how the ethos of open technical knowledge, which is central to Lasersaur and other projects, is in tight entwinement with the 'technical

[7] A similar conception of technical innovation is put forward by Arthur (2009).

mentality', as Simondon would call it. In a profound sense this is an ethos of modularity based upon digitised and public knowledge.

Modularity is also important in social terms. The Lasersaur project draws upon already existing services, objects, media and organisational forms that enable the forming of public groups and the communication amongst them. Furthermore, in drawing upon the knowledge of the many in such groups, there is a certain modularity of knowledge and skills that are meant to add up. Not everyone has to be able to create knowledge about each step, yet almost everyone is required to use the knowledge that is being created by others and to make this correspond with their local contexts and technical objects. Furthermore, the Lasersaur project projects itself in imaginative and practical ways as a module into an unfolding collective machine of open digital fabrication including many projects, in which there is and shall be an increasing publicness of the circulation of digital explicit knowledge, capable machines and willing people in correspondence with them. Such tightly interwoven forms of digitally enabled modularity – in 'technical' and 'social' terms – creates a form of an 'open Internet of things and people' in which technical objects and people mutually inform each other and the information processes are highly networked and often public. Such a technosocial constellation is simultaneously producer and unfolding product of the TechKnowledgy of open digital fabrication. This TechKnowledgy provides procedures that create and perform all aspects of technical becoming – desire, development, transformation, use etc. – as malleable through and visible in particular digitised publics that circulate technical objects in various forms. In the next chapter on FabLabs I analyse how the TechKnowledgy of open digital fabrication has been unfolding together with FabLabs and how 'openness' is being experimented with in the entwinement of digital and material settings.

4 FabLabs: experimenting with organisational forms

FabLabs (‘fabrication laboratories’) have been amongst the most significant places for open digital fabrication. What initially started as a trial with public access to industrial machines at the Massachusetts Institute of Technology (MIT) around the year 2000 has turned into an estimated 700 FabLabs across the globe in 2016. Although these labs share the same name they are rather diverse and have been part of a process that also saw the mushrooming of similar organisations such as hackerspaces or makerspaces in the past years. There are FabLabs with formal ties to MIT, others without, some labs are run as a business and others as part of a host institution or as a non-profit organisation sustained and organised by its members. Besides this plurality, the differences and similarities of the other mentioned organisations are also part of this chapter. Despite this diversity, however, FabLabs typically claim to make the machines and processes of digital fabrication accessible to individuals and particular groups, often even to the public. In a typical FabLab you would therefore find some CNC machines such as 3D printers, laser cutters or milling machines and people using them for various purposes. This is at least the ideal that FabLabs strive towards: opening digital fabrication to audiences and users beyond industry and academia. In FabLabs the TechKnowledgy of open digital fabrication is, thus, particularly visible, especially so as FabLabs have been involved in defining it. Organising a FabLab is about organising people, machines and knowledge. But how has the unfolding of FabLabs taken place?

Within the collective process that boosted and diversified FabLabs from a handful to around 700 in about a decade, ‘grassroots’ FabLabs stand out in particular. These labs with comparatively limited financial resources have been run by their members or have otherwise been set up as civil society organisations that try to facilitate the usage of digital fabrication for enthusiasts, hobbyists, small-scale enterprises or even children. They draw on ideas of decentralisation, individual empowerment and networking that have been championed by Internet utopianism and mix these with forms of organisation and formations of the material world. This chapter is mainly based on an analysis of the first years of FabLab Karlsruhe, a grassroots FabLab in Germany that I helped to set up as an action researcher, whose construction is analysed here. FabLab Karlsruhe, however, does not stand on its own. The preconditions for the lab’s existence and unfolding have to be sought in the collective process that all FabLabs have been entwined with. The analysis of FabLab Karlsruhe is, thus, also embedded in an analysis of the history and spread of FabLabs, i.e. the collective machine that has been unfolding with FabLab Karlsruhe as but one element.

How was the foundation of FabLab Karlsruhe possible and how has it been unfolding? This question is not that straightforward to answer. FabLabs are curious organisations, inherently diverse and difficult to clearly map onto the institutional domains of contemporary society. Any answer to this question, therefore, needs to consider that the current FabLab assemblage had not been planned, that many different actors have become involved in co-defining this collective machine over time and that its configuration created many surprises and novelties. I argue that FabLab Karlsruhe was possible because the collective machine of FabLabs has been unfolding in the mode of a ‘real-life experiment’ (cf. Krohn and Weyer, 1994) based on many different interventions that sought to foster digital fabrication beyond industry and academia. The collective FabLab real-life experiment has been important in co-defining the TechKnowledgy of open digital fabrication. FabLabs are places that, similar to digital fabrication machines, mix digital and material spheres, yet particularly so in terms of organising these machines and people.

This chapter analyses how FabLabs have become real-life experiments and what the elements and processes that have entwined with the collective machine of FabLabs are. Through this, the chapter also asks how stability and guidance met with creativity and change that enabled the quick spread of FabLabs. The chapter, first, discusses the theoretical instrumentarium that enables me to consider real-life experimentation as part of the TechKnowledgy of open digital fabrication. Second, in a historical analysis the emergence of the initial FabLabs at MIT is being analysed and how this resulted in a dynamic machinic assemblage that became set to transcend the confines of MIT. Third, the first years of FabLab Karlsruhe are analysed as part of a collective experiment that transcends this local organisation. This entails a discussion on the possibility to intervene in the becoming of open digital fabrication as action researcher.

4.1 Real-life experimentation

Addressing open-source practices or even FabLabs as an experiment is not absolutely new. Kelty (2008) in his wide-ranging study of free and open-source software speaks of it as an experiment in the changing relations of knowledge and power. Yet, besides metaphorically speaking of an experiment, Kelty does not delve deeper into describing the actual processes of experimentation and what makes them possible. Troxler also metaphorically speaks of a FabLab experiment (Troxler, 2015). Dickel et al. (2014) went further and described FabLabs and makerspaces as real-life laboratories and investigate two cases of innovative practice for which these organisations provided the experimental setting. This chapter extends these perspectives and investigates the history of FabLabs in general and of a particular FabLab, FabLab Karlsruhe, as a collective real-life experiment. What are the features of such real-life experiments?

Krohn (2007c, 2007a, 2007b) argued for the following key characteristics of real-life experiments. There are actors that address and intend to change a particular societal situation, arrangement or process. The actors intervene in this arrangement and expect to influence it in a particular way, even though they need not call this an ‘experiment’. The consequences of the intervention are being observed and analysed to enable recursive learning amongst the actors, such that they are better able to handle the processes and their interventions. Real-life experiments are trials to find or improve solutions to real-life problems whose construction can already be seen as a step towards experimentation. These activities need not necessarily be taken by the same actors; rather, there can be a division of labour amongst an only loosely coupled group of actors. As collective processes real-life experiments have porous borders. What and who influences real-life experiments, and what they affect, is neither clear-cut nor pre-given. They are part of the complexity of the social world and can dramatically change over time.

The recursive learning process is also addressed by Rheinberger (1997) in his theory of scientific experimentation. Rheinberger points out how experiments work with unfolding and not yet fully known ‘epistemic things’ that are enabled by an arrangement of ‘technical objects’. In the process of learning about epistemic things, the experimenters also learn to handle them better they might become technical objects themselves that enable further experimentation. Rheinberger compellingly points out the role of objects as enablers of experimentation, but since he studied scientific laboratories, he took the organisation beyond these objects for granted. As the chapter will show below, experimentation with organising is important in FabLabs. Rheinberger, however, points out a defining attitude of experimentation in or outside the laboratory: experiments are processes to create and deal with surprises. One could say, real-life experiments arrange people, knowledge, skills, objects and organisations in the mode of ‘what if?’. They walk the fine line between determinacy and indeterminacy and keep things unfolding in a surprising manner. Real-life experiments are therefore practices of ‘future-making’ (cf. Adam and Groves, 2007). They actively mediate past and future, what was and what is not yet (which is much more than what is explicitly imagined) in the present (cf. Bloch, 1995). Experiments are an effect of the future on a present in becoming; they ‘give the future a try’.

Experimentation in various shades and various areas of society is a key principle in modernity. Accordingly, the semantics of experiment can be found in many areas of modernity, such as art, war, science, politics, in both positive and negative uses (Krohn, 2007d). The heightened rate of change, the question of 'innovation' and profit, the rise of modern science, the increase in technologies and potentials to modify them have been creating much experimentation. Modernity has created the experience that there is constant human-created change, that 'all that is solid melts into air' (Berman, 2010; Marx and Engels, 2002; Bauman, 2000). At the beginning of this experience, Francis Bacon justified scientific and technological experimentation as a mode to improve society and laid the philosophical foundations for modern technoscience (Schmidt, 2011). It is noteworthy to remember that 'experiment', 'expert' and 'experience' are semantically closely related. However, real-life experimentation is not simply a translation of the scientific experiment into society; rather, it emerged in conscious practices of transformation that had to deal with non-knowledge and learning in a contingent world that became increasingly malleable through human action.

Experimentation also found its way into political philosophies that see it as an important and desirable way to strive for social change. The chapter on TechKnowledgy already discussed how Deleuze and Guattari's conception of machinic assemblage is sympathetic to an experimental mode of becoming. Theirs can be read as a politics of experimentation in a dynamic and indeterminate world. Also Popper (Krohn, 2007a; Popper, 1971), prominent through his philosophy of scientific experimentation, argued after the Second World War against totalitarian states and their planned and enforced transformations of society. Against these 'closed societies' he set 'open societies', which only strive for confined and incremental change through experimentation. He saw open societies realised in liberal democracies and capitalist market economies. Popper actually was a conservative and became one of the intellectual founding fathers of neoliberalism. However, his thoughts were also influential in shaping the liberal ethos of 'openness', which is not the same as neoliberalism (Tkacz, 2015). From a different political angle, the Marxist philosopher Ernst Bloch claimed that the whole world is an experiment in which humans take part (Bloch, 1975, 1995). An advocate of social progress, Bloch argued for an ethics of experimentation that would strive for equality, flourishing and a thorough transformation of the human condition. And somewhat similar to Popper he was opposed to systems of thought and practice that were grounded in static knowledge of the past or the present. Although advocating different goals and purposes, these authors agree on the method of experimentation for social transformation. However, Bloch saw that the capitalist societies were not as open and democratic as Popper liked to think and, therefore, advocated for large-scale change in contrast to Popper's 'piecemeal engineering'. But the politics of real-life experiments are not confined to intellectual debates. As Krohn (2007d) points out, real-life experiments are always contested modernisation projects; there is a 'priority of the political'. They affect and intend to change the lives of people and are contested. Questions of who is able to experiment and by what means and for what purposes are crucial to understand the politics of experimentation.

Even in the field of STS different meanings and purposes were ascribed to them and they were mobilised as political processes. When in the 1980s sociologists of science and technology started to address the experimental character of technology and innovation processes this was a critical move, emphasising mainly negative aspects of experimentation (Krohn and Weyer, 1989, 1994). It was a move that was made in an intellectual climate dominated by the 'risk society' that industrial societies have formed (Beck, 1992) and an anti-utopian 'heuristics of fear' (Jonas, 1984)[1]. Conceptually, the move was against linear ideas of technological innovation as the mere application of science against understandings of modern technology as stable and determining, as simply instrumental reason; basically the move pointed towards the 'unruly' and risky experimental character of technology (Wynne, 1988). Thus, when society has become a 'laboratory' experimental knowledge production cannot be confined to bounded settings 'outside' society, such as

[1] This was explicitly elaborated against the 'heuristics of hope' in Ernst Bloch's philosophy (1995).

the scientific laboratory. Rather, experimentation takes place ‘in’ and ‘with’ society because of the complexity of social life where non-knowledge is paramount. Groß (2016) even shows how real-life experimentation precedes laboratory experiments that try to work out solutions to problems that appeared in real-life experimentation.

About twenty years later, the notion of ‘real-life experiment’ was enjoying a comeback. Now, however, many authors use it as a positive concept with a problem- solving outlook for contemporary society. In the famous report on the European knowledge society, the authors advocate ‘collective experimentation’ to find novel ways of innovating in society beyond the dominant ‘regime of economics of technoscientific promises’ (Felt et al., 2007). Other authors similarly argue that to successfully deal with emerging technosciences, e.g. synthetic biology, society needs to engage in real-life experiments (e.g., Nordmann, 2014). While the diagnosis is still that there is something wrong with society and its technology, real-life experimentation is now being seen as a potential way out, a way to learn and to change society. Real-life experimentation is considered to be a procedure able to constructively deal with non-knowledge (e.g., Groß, 2010) and to transgress the shortcomings of dualist thought and institutions based on it, which assume strong differences between knowing and acting, theory and practice (e.g., Bammé, 2014; Bogusz, 2012). The central question seems to no longer be whether there should be experimentation but whether experiments are well or badly designed (Latour, 2011).

Below I turn towards the initial design of the FabLab experiment at MIT and particularly focus on its politics. To understand what started the FabLab experiment and what kept it growing through being taken up by diverse actors it is central to understand how FabLabs became desirable to these actors in the first place. The next section turns towards the emergence of the idea for FabLabs and the processes that turned it into a vision for the future that was desired and turned into experimental interventions.

4.2 Desiring FabLab experiments

Real-life experiments are conscious and desired interventions into the world. And although they are creative processes in themselves, engendering surprise and new knowledge, initial ideas for these interventions have to come from somewhere at first. For real-life experimentation there need to be visions and imaginations of what such experimentation might and should be good for, engendering desires for experiments. Extending the analysis of processes of creating and spreading desires in open digital fabrication in the Lasersaur chapter above I turn to the desires of FabLabs. Desires that are mediated by visions are an integral part of real-life experiments and it’s not that the time of visions is over when real-life experimentation has started (Lösch and Schneider, 2016). Whilst with ‘visions’ I designate positively framed imaginations of the future, real-life experiments mediate such imaginations with creative and practical processes in which particular interventions are tried out to foster change which might also influence imaginations. Real-life experiments, thus, assemble desiring machines that try to create trajectories of becoming. What is the collective machine in which FabLabs came into existence and how did it visioneer FabLabs as something desirable to be realised in the future? How was a desiring machine created that started experimentation with FabLabs? The following parts analyse the visioneering of FabLabs in a move that focuses on the birth of the initial idea first and traces the machine within which this idea began to circulate and change over time.

4.2.1 Surprising technoscience

The person who is most often seen as the 'inventor' of FabLabs is Professor Neil Gershenfeld. The start of FabLabs is often said to be the MIT's Center for Bits and Atoms (CBA), where the first FabLab was initiated by Neil Gershenfeld, the center's director, in 2002. Gershenfeld is often depicted as the genius and the visioneer behind FabLabs, such as by one of his colleagues at MIT:

> 'So Neil still pulls the strings but he is the founder, it is his vision and frankly where he sits intellectually is 5-10 years ahead of what he is doing [...] this is why I still call this an experiment. He is the only one sitting outside the petri dish' (Chris Wilkinson quoted in Hielscher et al., 2015a, p. 26)

This is a person of Fab Foundation, an MIT-based organisation for FabLabs closely working with Gershenfeld, who articulates the individual hero narrative that I will challenge in this analysis. Whilst Gershenfeld has an important position in FabLab history, he is certainly not the experimenter overlooking everything. Instead, I will analyse how Gershenfeld has been part of a collective machine of imaginations, science funding and various practices that all contributed to the emergence of FabLabs. The discursive and practical roots of FabLabs can be traced to other sources before and beyond Gershenfeld. The FabLab real-life experiment didn't start out of the blue, but has a complex history. This part analyses this history as a form of collective visioneering that created desires and focuses first on the emergence of the initial FabLabs at MIT around 2000 – which is a history of surprise and the experimental reworking of technoscientific routines.

An important source of the FabLab vision came into being in post-WWII USA in a mix of early technoscience and countercultural movements and is analysed by the historian Fred Turner (2006) in an excellent analysis of visioneering activities. I discuss Turner's history in some length, since it shows how imagining the future is not only in representations, and that it can turn into practical future-making. Turner shows how certain 'hippies' in the late 1960s believed in the power of new 'tools' (computers, narcotics, cybernetic theories etc.) to create a new consciousness and new non-hierarchical communities. He goes on to show how in particular one of them, Stewart Brand, was successful in creating the 'Whole Earth Catalogue' (its first edition in 1968, subtitled 'Access to Tools'[2]). Related to this publication, Brand brought into being 'network forums', in which different communities could interact and mix countercultural, scientific, technological and entrepreneurial ideas and practices over the years. This process, by the late 1980s, had created powerful discourse and supporters in the US of an Internet utopianism, which heralded the Internet as a prime source for a new society. Besides creating certain semantic framings of the Internet it influenced organisations and technologies. Its consequences were formed in a transformation from 'counterculture to cyberculture'.

> 'Brand's entrepreneurial tactics, and the now-widespread association of computers and computer-mediated communication with the egalitarian social ideals of the counterculture, have become important features of an increasingly networked mode of living, working, and deploying social and cultural power. Although it is tempting to think of that mode as a product of a revolution in computing technology, I argue that the revolution it represents began long before the public appearance of the Internet or even the widespread distribution of computers. It began in the wake of World War II, as the cybernetic discourse and collaborative work styles of cold war military research came together with the communitarian social vision of the counterculture' (Turner, 2006, p. 9).

2 Such access to tools in a different sense is nowadays widely called for in the open source culture, where access to information, from Wikipedia to building instructions, is a key principle and value.

Amongst the people in the visioneering circles that Turner describes were people with a high level of influence on computer technologies and discourse surrounding them, such as Kevin Kelly, who launched ‘Wired Magazine’, the leading popular magazine concerning digitisation in the USA, and Nicholas Negroponte, who was the founding director of MIT’s Media Lab, established in 1980, the organisation that later on would initiate Gershenfeld’s CBA. In the 1980s, Brand was at the Media Lab for a couple of months and even wrote a book about his experience:

> ‘[Brand] depicted the Media Lab and its digital technologies, as well as Negroponte and the corporate and research cultures within which he worked, as prototypes of an emerging socio-technical world. [...] the Media Lab made digital-social hybrids; its culture was itself a hybrid of digital and cultural workers; the world that its research would produce would be infused with such hybrids [...] the Lab demonstrated the way a “wired” world might look’ (Turner, 2006, p. 180)

When Gershenfeld started FabLabs, the Media Lab within which Gershenfeld worked had already been a central hub in visioneering and desiring digital technologies as liberating. How did the idea of FabLabs emerge there? In the following, I will focus on documents closely related to Gershenfeld in the early times of FabLabs and link them back to other sources that have been mobilised in FabLabs. Gershenfeld has been an influential professor at MIT and, thus, it is not surprising that the cultural ideals of technoscience were mobilised initially. But this happened with an interesting shift that I analyse first, taking the official MIT news of the launch of the CBA (MIT News, 2001) and Gershenfeld’s book (2005) on FabLabs and personal fabrication as prime sources and as documents of the efforts to visioneer FabLabs as desirable – at least to people minded like Gershenfeld and colleagues[3]. The interpretation of this early FabLab vision links discursive utterances to other practices and historical predecessors.

In 2001, Media Lab received a grant by the National Science Foundation (NSF; a governmental organ for science funding in the USA) of $13.75 million to bring ‘nanofabrication, chemistry and biology labs together with rapid mechanical prototyping, electronic instrumentation and high-bay assembly workspaces’ (MIT News, 2001) in the CBA. As Nicholas Negroponte is quoted in the news article: ‘When we started the Media Lab, the interesting question was how bits and atoms differed [...] Today the interesting question is how they are the same, how they come together’ (MIT News, 2001). Thus, the Center for Bits and Atoms aims to investigate and foster the interplay of physical and informational sciences and the ‘researchers are seeking radical applications and understandings of information technology. NSF’s mission is to support just this type of basic science’ (MIT News, 2001). Already in this news text, the CBA is clearly positioned within the culture of technoscience as analysed by Nordmann (2010, 2011, 2012): the CBA works in an interdisciplinary and problem-oriented way towards the combination of bits and atoms; in contrast to ‘classical’ science, it seeks first new technological capabilities – using things, ‘applications’ – and only second ‘understandings’ – explaining things theoretically. That it also seeks to be ‘radical’ with technology, furthermore, suggests that the CBA aims to bring about changes through the new technological capabilities – it has an instrumental relation to the ‘world’. Technoscience regards research ‘as knowing by doing, as a means to create and realize technical potential and thus to construct the world we live in’ (Nordmann, 2011, p. 28). And the CBA is no exception to that.

Gershenfeld had already been working on one idea for such ‘radical change’ when the news declared that among ‘the challenges to be tackled will be developing “personal fabricators” to bring the malleability that personal computers provide for the digital world into the physical world’ (MIT News, 2001). To further

[3] Unfortunately, empirical research on the initial phase of FabLabs hardly exists. And besides Gershenfeld’s own account there is a study about the founder of one of the first FabLabs beyond MIT in Norway (Kohtala and Bosqué, 2014) and interview quotes of other people involved at MIT in another research project (Hielscher et al., 2015a).

research on personal fabricators, Gershenfeld and colleagues put together ‘millions of dollars worth of machinery’ to assemble ‘an array of machines to make the machines that make machines’ (Gershenfeld, 2005, pp. 7, 5). Why this effort? Gershenfeld, at least in his book, is inspired by the visions of nanotechnology. He quotes Eric Drexler’s vision of self-replicating nano-machines and the related dream to have a machine that makes ‘anything’ in a world where in principle everything is seen as programmable. Furthermore, Gershenfeld draws parallels to computing, where small, personal machines replaced the large mainframes for experts – a move that Gershenfeld is sure fabrication technology will also make. The faith in technology and technological progress to bring about radical change is common in technoscience and its visioneering (Grunwald, 2014; Nordmann, 2013; McCray, 2012).

But in 1998, the reality was that the set of machines that were assembled to create personal fabricators were difficult to use. Thus, the idea was to launch a practical introductory course for graduate students entitled ‘How to Make (Almost) Anything’ to enable them to use the machines for their research. This course would become the birthplace of FabLabs. As Gershenfeld describes it, instead of a few graduate students, about 100 students from all over MIT were excited to do this course, yet not to do research but to use the digital machines to create things. Gershenfeld writes about four surprises that these courses created for him and relates them to particular ideas. I trace and analyse these here since they constitute the initial narrative with which FabLabs were made desirable.

The first surprise Gershenfeld narrates is that there was a large level of interest among students ‘with relatively little technical experience’ (Gershenfeld, 2005, p. 6). While this resonates with the interdisciplinary and project-centred practices at Media Lab as described by Turner, this also resonates with other cultural elements. On the one hand, the highly specialised and differentiated industrial, technological and scientific systems of modernity produce strong divisions of labour and its corresponding specialised ‘experts’ (Morin and Kern, 1999; Giddens, 1991; Noble, 1984; Mumford, 1970). This, however, has been countered with positive valuations of practices that transgress such divisions and of people who are or become ‘lay experts’ in certain settings (for science Wynne, 1996). Furthermore, in contemporary society many technical objects transgress professional contexts and offer their unfolding to new subjects who find sources of self and sociality in such (technological) objects and become ‘experts’ in them (Knorr-Cetina, 1997). Gershenfeld’s positively depicted surprises in a way also value these new subjects.

The second surprise was that the students were not there for professional reasons, but it ‘was their own pleasure in making and using their inventions’, and with this they ‘were inventing a new physical notion of literacy […] for technological expression every bit as eloquent as a sonnet or a painting’ (Gershenfeld, 2005, pp. 6–7). Here, Gershenfeld mobilises what Boltanski and Chiapello call ‘artistic critique’ which ‘vindicates an ideal of liberation and/or of individual autonomy, singularity, and authenticity’ (Boltanski and Chiapello, 2005, p. 176). This can be traced back to 19^{th}-century romanticism, and ‘technological expression’ was also highly valued in that same century’s ‘arts and crafts movement’ in the UK for example[4]. And of course, Boltanski and Chiapello’s argument is that the ‘new spirit of capitalism’ equally promotes such individuality in workers and consumers – to its own ends. This form of critique was also crucial, however, in the US counterculture, and even today it finds enough spheres of social reality where it can identify shortages of that which it strives for.

Gershenfeld’s third surprise was somewhat similar to the first; it is about ‘what these students managed to accomplish. Starting out with skills more suited to arts and crafts than advanced engineering, they routinely and single-handedly managed to design and build complete functioning systems’ (Gershenfeld, 2005, p. 6). In industrial settings, Gershenfeld argues, individuals were not able to accomplish this, tied as they are to

[4] See William Morris’s *News from Nowhere*, published in 1890, as an important form of visioneering for that movement in the form of a novel.

divisions of labour and hierarchical collective processes. Besides this explicit critique of industry, Gershenfeld implicitly appraises the technosocial setting this course enabled, where it is possible for people and machines together to individually produce something from scratch. The things, however, produced in Gershenfeld's course and many other FabLabs are not (yet?) of the complexity of industrial objects such as smartphones or cars. But they do not need to be. For Gershenfeld 'personal screaming technology' (Gershenfeld, 2005, p. 7), basically a pillow that records sounds and plays them, also a scream if you want, is one of the examples he gives that is enough to show to him the basic capability of this setting where '(almost) anything' can be made, where the potential of particular digital technologies is experienced. Again, a cultural ideal of technoscience is mobilised which strives for the demonstration of a new technical capability (cf. Nordmann, 2012).

Fourthly, Gershenfeld was surprised by the learning approach the students used. Initial learning by trial and error was followed by mutual sharing of knowledge where the students passed their knowledge on to their 'peers' to do just what they needed or wanted to do. Such a 'teaching on demand' model, Gershenfeld argues, is different to what universities typically do with fixed curricula and often not directly useable knowledge (Gershenfeld, 2005, p. 7). Besides the critique of hierarchical institutions, now in its third shape, Gershenfeld emphasises the communitarian ideals of solidarity, sharing and equality, and how they are almost cybernetically created in the course's technosocial setting. This again draws on resources analysed by Turner, a mix of counterculture and digital technology, beyond the MIT also often depicted as 'peer-to-peer' processes and also influenced by much older anarchist cultural currents (e.g., Benkler, 2013). While this might be an idealisation by Gershenfeld, the massively overcrowded course suggests that there were such learning processes if the students actually got something working out of the machines.

In 2001, when the CBA started, there was accordingly much going on concerning 'personal fabrication' and experiences with people using prototypical arrangements of such technologies. The funding by the NSF, however, also required 'outreach' elements. And Gershenfeld became the coordinator of 'the technical program for Media Lab Asia, which was established this year [2001] in India to explore appropriate information technology for economic and social development. These partner efforts will both ground the center's research and provide channels to bring its results beyond the laboratory' (MIT News, 2001). What should be explored were 'fab labs'. Inspired by the class at MIT, Gershenfeld wanted to 'deploy proto-personal fabricators in order to learn now about how they'll be used instead of waiting for all of the research to be completed' (Gershenfeld, 2005, p. 11). With a couple of commercially available machines with a combined value of around $20.000 ordinary people were to be equipped 'to actually do what we're studying at MIT instead of just talking about it' (Gershenfeld, 2005, p. 12, italics in original). Thus, in 2002, the first FabLabs were launched in 'rural India, Costa Rica, northern Norway, inner-city Boston, and Ghana' (Gershenfeld, 2005, p. 12).

The selection of these first locations for the labs, however, was not random but carefully chosen. In their ethnographic description of the Norwegian FabLab Kohtala and Bosqué (2014) point out the crucial role of the lab's founder. Being an inventive sheep farmer, the founder was noticed by MIT in the late 1990s and Gershenfeld even collaborated with him to improve his electronic and GPS-powered sheep sensor. The two became friends. The Norwegian man was well-known in his community and went on to develop the FabLab as a sort of multipurpose community centre. He, furthermore, was involved in the early discussions about FabLabs at MIT, which were influenced by his community orientation. Therefore, far from simply trying out what 'ordinary' people would do, the spread of the initial labs was a careful process of visioneering that even selected the people who were seen as suitable for a cooperation with MIT and for promoting the concept in their local contexts.

By setting up three FabLabs in poorer countries, the CBA became involved with discourse and practice of 'appropriate technology' (cf. Mikhak et al., 2002). Strongly inspired by writers such as Ivan Illich (1973

'Tools for Conviviality') or Schumacher (1973, 'Small is Beautiful'), this sphere has been aiming at technologies alternative to industrial arrangements and 'appropriate' to local needs. Although this began as a critique of industrial Western society, approaches, practices and experiments with appropriate technology were from the 1980s onwards mainly focused on developing countries (Kaplinsky, 2011). The discourse on appropriate technology, however, was also influential in the Western environmental movement, where it was conducive to local and small-scale agriculture or renewable energies, for example. The MIT and Gershenfeld, however, combined their appropriate technology approach with information and communication technologies. In 2002, a group including Gershenfeld presented their initial FabLabs in a conference paper: 'At the heart of this idea is the belief that the most sustainable way to bring the deepest results of the digital revolution to developing communities is to enable them to participate in creating their own technological tools for finding solutions to their own problems' (Mikhak et al., 2002 n.p.). They give much thought to ICTs and possible designs of technologies suitable for FabLabs and emphasise that FabLabs aim to enable people to actually use these technologies. This shows a Western techno-progressivist idea that technology should (and will) do 'good' to 'poor' societies[5], and this is entwined with an emphasis on the social use of technologies and, thus, points towards another element that is mobilised initially.

The FabLabs in Boston, Norway and India were about giving public access to the machines arranged and also to enable people to use these machines towards their own ends. This resembles the key idea of communism as it developed through the centuries: the community of goods (Eßbach, 2011). As Eßbach shows, this was initially created in the ancient Greek polis, which showed its radical (social and technical) artificiality and, thus, contingency to (some of) its observers. It was considered that the relations to technologies and the political relations to others had an effect on each other and that the conscious design of these relations, e.g. shared households, might also lead to an improved community in the city. The community of goods has in many ways during history been an intellectual product and is currently having a fresh wave of support and creativity – the 'commons' and mainly the new Internet-enabled commons receive much attention (Rifkin, 2014; Bollier and Helfrich, 2012; Gorz, 2010b; Hardt and Negri, 2009; Benkler, 2006). Furthermore, the FabLab experiment was not for profit-making initially but to investigate possible transformations in the relation of 'technology' and 'social' organisation. Curiously, although initially based on the vision of individual 'personal fabrication', FabLabs from the beginning enacted 'communal fabrication', common[6] instead of private usage of these machines. In this respect, the initial discursive framing of the labs differed from the actual practices that they were based on. However, my analysis will show – especially in the chapter on experimental economies – that the particular way in which the commons of FabLabs has become mobilised by MIT is strongly directed towards business. For now, it is sufficient to note that the commons prominently featured in the initial FabLab vision at least.

In this context it is interesting how Gershenfeld (2005, p. 25) uses a mix of images and visionary narrative to present the concept. The images in the book show FabLabs as relatively low-cost workshops with mainly young people. Some small-scale machines and personal computers stand on untidy desks. It seems as if one would look in a class room at high school. What is presented as a FabLab could actually be seen as 'just' three desks and three small machines with which people are working. But for Gershenfeld this is enough; they show the actual feasibility, the technosocial capability that was created by FabLabs – the products themselves are not that important. Hardly 'anything' can actually be made there. Here, Gershenfeld is also hardly a typical technoscientist interested in controlling novel technical capabilities (cf. Nordmann, 2012).

[5] Gershenfeld is in prominent company at the Center for Bits and Atoms: Negroponte, the founder of MIT's Media Lab, received a lot of renewed attention in 2006 when he launched the 'one laptop per child' project, which aimed at providing children in developing countries with cheap and robust laptops.

[6] The word common shares etymological roots with 'commune', 'communism', 'communal', 'community'. They point towards the social relations that are constitutive of something shared or of something public.

Actually, there are hardly novel technical capabilities but novel ways of organising a set of rather inexpensive industrial machines, standard, nothing particularly cutting-edge about them. Yet Gershenfeld deploys this localised and confined proof of concept into a typical technoscientific narrative that promises linear growth and impact, such that the future is seen as a space where ‘anybody can make anything anywhere’ (Gershenfeld, 2005, 2012). Nordmann (2013) depicted this creation of ‘tunnel visions’ that suggest that A will lead to B through technological advances as typical of technoscientific visioneering. In the following I show, however, how the activities of making FabLabs desirable transcended MIT and how this also transcended ‘typical’ technoscience, as criticised by Nordmann.

4.2.2 Surprising spreads

Besides this initial narrative a dynamic started that set the machinic assemblage which had been desiring FabLabs on a deviant course from typical technoscientific visioneering: a deterritorialisation changed the practices and consequences of FabLabs. Although Gershenfeld was spreading his narrative through his book in 2005 or his popular TED talk in 2006 (Gershenfeld, 2006), he was aware that it is no longer him and MIT that are in control of FabLabs. In 2004, there were 32 FabLabs, a number which had increased tenfold by 2014 (Troxler, 2014). Indeed, seeing this early growth, Gershenfeld admitted in 2005 that he is but one visioneer in a larger process: ‘fab [his 2005 book] would not have been written, or been worth writing, if not for the unexpected global growth of fab labs, which has been one of the most rewarding activities I’ve ever been involved in. […] [FabLabs are] growing beyond what can be handled by the initial collection of people […] I/we welcome your thoughts on, and participation in, shaping their future operational, organizational, and technological form’ (Gershenfeld, 2005, pp. 258, 264). The growth of FabLabs in these years, however, involved formal relationships to MIT, even including fees, and state-financed programmes, for example a FabLab programme by South Africa’s government.

The scale and quality of the growth of FabLabs, however, started to become more radical in 2007. Troxler (2014) describes how in the Netherlands in 2007 a FabLab Foundation was set up, with the agreement of Gershenfeld, that wanted to spread FabLabs in the Netherlands without taking part in MIT’s outreach programme. The FabLab model, however, still involved setting up a Lab with a budget of about €100,000, as promoted by MIT. In 2010, this changed when a group of artists in Amersfoort, the Netherlands, inspired by community-organised formats and visions of a ‘peer-to-peer society’ set up their FabLab with about €5,000 and cheap machines, mostly self-built open-source versions (Hielscher et al., 2015a, chap. 4). This was the first ‘grassroots’ FabLab and it was followed by many others, which caused a massive deterritorialisation of the FabLab assemblage, opening up its centralisation around MIT and in turn creating new lines of becoming, possible trajectories for it to unfold. Gershenfeld and MIT, with only limited personal resources, could not keep up with the mushrooming of further FabLabs without formalised relations to MIT and only slowly adopted ‘low-cost’ FabLabs into their online documentations of what a FabLab ‘is’ in their view (Hielscher et al., 2015a, pp. 23–24; Troxler, 2014).

Looking back, Gershenfeld summarises his surprises about this spread of FabLabs in a documentary film:

> ‘At Fab1 [in 2004] we were ten people at MIT and thought we would never meet again [...] Hakan a crazy guy started his lab above the arctic circle [...] and we had a meeting there [...] the meeting in Chicago, called it Fab4 only as a joke because there was a film out called Fab4 [in 2007] [...] we thought we were done but [the number FabLabs] kept on growing bigger’ (Gershenfeld quoted in Hielscher et al. 2015 p. 14)

For a couple of years, thus, FabLabs have been moving beyond the experimental setting that MIT established; nowadays, ‘high-cost’ and ‘low-cost’, state run and grassroots FabLabs spread around the globe, assembling with different settings and together defining the real-life experiment and its further unfolding.

Estimations of how many FabLabs there were around 2014 and 2015 vary between 350 and 440. In summer 2016, the list of FabLabs at a FabLab networking site counts 692 FabLabs (https://www.fablabs.io/labs, accessed August 2016). Amongst these FabLabs, roughly three different types can be distinguished. A first type are FabLabs hosted by a larger organisation or institution, such as by MIT or a foundation. Second, some FabLabs have been set up as an independent company. And third, there are grassroots FabLabs organised by bottom-up initiatives and not primarily seeking profit, such as FabLab Karlsruhe. And in fact, concerning their financial resources and organisational styles, there are huge differences amongst these labs, although roughly they follow the concept of providing access to digital fabrication (Lhoste and Barbier, 2015; Hielscher et al., 2015a; Troxler, 2014; Kohtala and Bosqué, 2014). Furthermore, during the past decade, so-called makerspaces and hackerspaces have spread around the globe as well. And although they have other histories and genealogies, more rooted in grassroots practices, these organisations similarly foster tinkering, experimentation with and access to digital technologies and digital fabrication (Hielscher et al., 2015b; maxigas, 2012). A comparison of the online self-descriptions of FabLabs, makerspaces and hackerspaces found that often the presentations are rather similar, focusing on individual tinkering and hacking of and with digital technologies (Van Holm, 2014). Seen in this light, FabLabs have to be seen within a larger machinic assemblage that has been fostering the emergence of unconventional organisational forms and social practices concerning mostly, but not only, novel digital technologies.

Therefore, as soon as FabLabs were out in the open, the visioneering that has been defining them had left the typical paths of technoscientific visioneering, which often operates in the circuits of technoscience, business and government to enact a ‘regime of economics of technoscientific promises’ (Felt et al., 2007). Different types of FabLabs have been experimenting organisational forms and technosocial processes around digital technologies. Lhoste and Barbier (2015) describe, for example, how in France FabLabs hosted by an institution have been changing the organisational rules and codes of the hosting institution through their goals and practices.

So, how did FabLabs come into being, how were they initially desired? The imaginative and practical activities that created FabLabs and desires for them were not entirely controlled and planned. The FabLabs vision was not a starting point that directed a project rather, this vision itself creatively emerged within a certain machinic assemblage that was mobilised by and itself mobilised particular cultural resources to energise a collective experiment in which desires were created and spread. Such visioneering has not come to a halt by now but is taking place in a global machinic assemblage that practically and imaginatively experiments with FabLabs. The history of FabLabs, thus, can indeed be seen as a history of surprises, created and dealt with in experiments.

At the Media Lab, a place full of technoscientific ‘future-making’, Gershenfeld and others pursued a technological vision of personal fabricators and wanted to find technical arrangements that might foster research on these machines. Rather typical technoscientists, they were trying to find novel technological capabilities with the support of industrial rapid prototyping machines. The students, however, with their enthusiasm about making stuff, added new meaning to this arrangement of machines. They provided a prototypical glimpse at a future in which ‘everyone could make (almost) anything’. Although the Media Lab historically provided such frames for technology, this comes as a surprise and unveils another potential of these technologies: their potential to make things people want to make, and their potential to be part of arrangements that are not only focused on technoscientific research. Along with the governance of NSF science funding, which required ‘outreach’ to bring results ‘beyond the laboratory’, the question and idea grew of what would happen if such a technosocial arrangement was set up beyond the confines of MIT. Thus, besides the technoscientific perspective on technological change and capabilities the experiences at MIT resonated with discursive and practical elements that further energised the process. The course ‘how to make (almost) anything’ and the initial FabLabs drew on ideas of technoscientific mastery, ‘lay expertise’, ‘artistic critique’, highly capable non-industrial approaches to technology production, self-governed peer-to-peer learning, appropriate technology and technology as common good. These different cultural resources – whether in combination or on their own – initially visioneered FabLabs as being desirable and worthwhile to try out.

The combination of the concept with these desires was even more successful than intended. The time had come for the idea. There existed an ecology within which the initial idea and concept could successfully materialise, spread and change and build a machinic assemblage way beyond MIT. Just to point out a few factors that contributed to this spread – more follow in the next chapter: the Internet and personal computers widely spread in the early 2000s in wealthier societies. Open-source software projects and projects such as Wikipedia showed the possibility of novel organisational forms through using the digitised infrastructure. A grassroots culture around software had developed in hackerspaces from the 1990s onwards (maxigas, 2012) and began to be transformed and widened by novel digital possibilities and practices (Kelty, 2008). More generally the emergence of the 'network society' (Castells, 2002) was increasingly being felt beyond business and research and created the sense that 'new media' create a 'new economy' and possibly a new society. Within a couple of years, the FabLab idea had been taken up by other research institutes, the media, initiatives from civil society and governments, businesses, MIT, open-source projects and more. They practically tried it out, linked it to other projects and aims, reported about it or criticised it. Through this they created a process of collective visioneering in which various actors tried to 'mobilize, explore, and push the limits of the possible' (McCray, 2012, p. 10). By now, Gershenfeld and MIT are but one element in this complex process; a collective machine that has been visioneering novel, decentralised and highly networked ways of organising digital fabrication machines to create experimental practices that do not fit into typical categories of, for example, research and business. This process has been performing FabLabs as desirable (or at least relevant to know about) for a growing number of people and organisations that experiment with them and, thus, feed back into the process.

Next, I focus on how a particular FabLab, FabLab Karlsruhe, came into being and how this related to the global machinic assemblage of FabLabs. I address the questions of how the FabLab vision and concept practically travel, how they are taken up, how they are embodied in FabLabs, how they are modified and how all this takes place in an experimental process.

4.3 FabLab Karlsruhe

To analyse FabLab Karlsruhe as an experiment within a larger experiment, I draw on an old idea in social theory by Gabriel Tarde. For Tarde, for society to exist and to transform, for social reproduction and social change, practices of imitation were crucial. Tracing similarities as well as diffusions of novelty in this perspective means tracing social practices of imitation. 'But, for Tarde, imitation was never exact. It always contained a potential surplus which allowed an event or an action to deviate into invention' (Barry and Thrift, 2007, p. 517). It was this creative understanding of the social that contributed to Tarde's rediscovery as a theorist of social innovation (Howaldt et al., 2015). In Tarde's words 'the real causes of change consist of a chain of certainly very numerous ideas, which however are different and discontinuous, yet they are connected together by even far more numerous acts of imitation, for which they serve as a model' (Tarde 2009 quoted in Howaldt et al., 2015, p. 38). Crucial here is that imitations happen in complex relationships and not only in the imitation of a single role model. Instead each imitation can become a source for another imitation. Tarde's ideas about imitation, however, contain a further important perspective for the analysis of FabLabs. Tarde placed great emphasis on sociotechnical arrangements such as the press or the telegraph that enabled desires and ideas to spread and functioned as a distributive infrastructure that enabled imitation across geography and society (Barry and Thrift, 2007). Absolutely central to FabLab experiments is the infrastructure of the Internet. It facilitates many forms of visibility of FabLabs where being seen and seeing and observing others via various social media and comparing one FabLab to another are important practices.

FabLabs via the Internet take part in a community of mutual observation[7]. However, the Internet is not enough to enable imitation. For FabLab practices to take place and be imitated there are complex and intersecting mobilities of people, information and objects (cf. Urry, 2007 for ‘mobilities’) that transport knowledge about FabLabs and make imitation possible such that collective machines can be formed across geography.

In the following I analyse how such heterogeneous flows made an experimenting FabLab Karlsruhe possible and how the practices of imitation contributed to the global FabLab experiment. Although I focus mainly on practices in FabLab Karlsruhe I also point out other examples not from Karlsruhe to highlight how particular dimensions of experimentation are inscribed into the machinic assemblage of FabLabs and how there are particular patterns and similarities. Through this, I show how imitation is a complex multidirectional process that enables a distributed collective real-life experiment. I present this process not in a strict chronological order but around certain characteristics, events and objects that highlight the dimensions of experimentation. First, I clarify my role in the foundation of FabLab Karlsruhe as action researcher and discuss this approach in relation to real-life experimentation. Second, I analyse how in Karlsruhe an initial machinic assemblage came into being and how this set the lab on a particular organisational trajectory. Third, the analysis turns to different dimensions of experimentation of the group that formed the lab with itself. Fourth, I focus on desiring again and analyse how this takes place in the FabLab with objects, projects and other organisations. Fifth, the chapter discusses how maintenance and repair are central practices that sustain experimentation. And sixth, I analyse how the FabLab experiments with different economic relations. The selection of each of these foci on the complexities of experimentation is justified at the beginning of each of these subchapters. Together they form a wide picture of how the TechKnowledgy of open digital fabrication is being experimented with in FabLab Karlsruhe and how this is partly enabled and influenced by processes and relations that go beyond the lab. Through the perspective on organising people, objects and visions the chapter shows how imitation is central to participating in globalised real-life experiments and learning from them.

4.3.1 Action research

My perspective on FabLab Karlsruhe is particularly influenced through my own experiment in research within the real-life experiment. I have a special relation to FabLabs and FabLab Karlsruhe in particular. I initiated the establishment of FabLab Karlsruhe in Summer 2013 and was engaged in establishing and organising it as an action researcher until early 2015, which turned me into a co-experimenter. This is also roughly the time frame that is analysed here. My involvement gives a special twist to this study and the following discussion of principles, methods, histories and justifications of action research shows why it is a fruitful method in real-life experiments. As action researcher I intervened in particular ways in the Karlsruhe experiment, but the readiness of the context to allow for these interventions also revealed the experimental mode within which the organising process found itself. These interventions are part of the analyses that follow in the chapters below. Now I discuss what action research is and justify it as a mode of research in real-life experiments.

[7] Creating arrangements of visibility is central to many different forms of modern sociality: Foucault (1995) describes the disciplinary effects of surveillance and of thinking that one is seen by others and how this creates normalisations of the subject. Sloterdijk (2016, ch. 2 C) points out how ‘collectors’ such as national assemblies, sports stadiums, parades and congresses create an enactment of collectives, when participants see the many others invested in the same activity. Szerzinsky and Urry (2006) show how different forms of visibility create a sense of citizenship and how due to increasing mobility of images and information the world is increasingly inhabited ‘from afar’. Related to FabLabs one could say with these arguments that mutual observation normalises FabLabs and that the Internet is the collector within which individual labs perceive themselves as part of a worldwide collective and they inhabit this collective from afar mostly through the screens of their PCs.

In a paper called ‘enacting the social’, Law and Urry argued that the social sciences have never been innocent. They participate in and enact a certain version of the social through helping to make particular realities and not others. And they do so, the authors argue, mainly in a way that is performative of 19th-century realities, e.g. of nation states and of bounded settings for the social. Now, to enact realities appropriate to the 21st century and a contemporary ontological politics, social science and its methods have to change.

> ‘[W]hich realities? Which do we want to help to make more real, and which less real? How do we want to interfere (because interfere we will, one way or another)? Such is the larger purpose of our intervention. The globalizing world is complex, elusive, ephemeral, and unpredictable. It is enacted that way without our help. But, if social science is to interfere in the realities of that world, to make a difference, to engage in an ontological politics, and to help shape new realities, then it needs tools for understanding and practising the complex and the elusive. This will be uncomfortable’ (Law and Urry, 2004, n.p.).

A particular approach to understanding and practising the social differently than in mainstream social science is action research. Action research, however, is neither a unified set of methods, nor a particular use of theory. Action research is an attitude that has ontological, epistemological, methodological and socio-political implications for the practice of research (McNiff, 2013). Doing action research means researching a certain field and acting on this field to have an impact for change. This implies not enacting the idea of science as a neutral, distanced and observing activity, but rather seeing it as something engaged in a world of flux (ontology). Such a stance entails a constructivist and situated understanding of knowledge (epistemology). It seeks to entwine knowledge production and research with the social situation in which it takes place (methodology). Also it aims to help make certain social realities and not others. It is a normative endeavour aimed at positive social change (socio-political). Obviously, action research breaks with positivist approaches to (social) science. As such, there are many sources that influence action research besides organisation studies where the term was coined in the 1940s. Particularly, critical social science such as Marxist or feminist approaches have influenced it strongly. Yet action research has also been practised in education research or management studies.

From these characteristics of action research a particular understanding of ‘action’ by the researcher follows. Acting in the social field cannot and should not be undertaken as an activity that tries to determine outcomes legitimated through ‘science’ that already knows what is best. The contextualised and participatory approach of action research demands an open, deliberative and egalitarian mode of action that sees the researcher as but one participant in a shared and collective process. What actions are appropriate in this process cannot be fully known in advance due to theory and research results. Instead, I like to understand my mode of acting in the social field as drawing on practical wisdom (cf. Flyvbjerg et al., 2012) that is informed through my socialisation as sociologist and through my ongoing observations and reflections on the field. Action research to me is about a mutual engagement in the world together with others, to provide one’s own questions and partial answers to collaboratively create new knowledge and influence practices. It has to follow an experimental approach that engages in co-experimentation with others, without trying to determine or to control the process. I see action research as an inventive approach, which might benefit sociology and social reality. Edgar Morin has been arguing that it is time for complex thought in society, where the separated fields of knowledge should be connected together again in a new way, appropriate to a complex world and its necessary transformation (Morin, 2008; Morin and Kern, 1999).

Although sociology mostly has forgotten about action research, there seems to be a wave of renewed interdisciplinary attention to this approach, as the launch of the journal ‘Action Research’ in 2003 (Brydon-Miller et al., 2003) and recent handbooks and entries in handbooks on methodology indicate (Dick, 2011). Furthermore, there are increasingly calls and approaches for social science and STS to become more engaged in social reality, to have an impact on change. One can think of transdisciplinary research, new forms of collaborative interdisciplinary research (Niewöhner, 2015; Rabinow and Bennett, 2012), the discourses on ‘responsible research and innovation’ (e.g., Owen et al., 2013) and on ‘transformative science’ (Schneidewind et al., 2016) that want to foster modes of research that transform the ways in which modern society has been innovating, or the call for a ‘public sociology’ which is more visible and helps to find conditions for flourishing in dialogue with publics and civil society (Burawoy, 2005). And there are increasingly voices, such as Law and Urry’s above, that call for a new creativity with sociological methods to face the contemporary realities and enact a different form of sociology, e.g. to become more ‘artful’ and ‘crafty’ as a ‘live sociology’ (Back and Puwar, 2013). Instead of advocating a particular legacy of action research or of sharply distinguishing it from other approaches I locate it within this contemporary tendency to rework social science and to rediscover its more engaged traditions.

Clearly, action research involves the researcher to a great extent in the process of acting in a social situation. This is inevitably normative. Nonetheless, this can and has to be reflexive as well. In an autoethnographic take below I make transparent what motivated me to do this particular research project and which values have been important to me during the process. Sociology could in many ways be more normative, benefit from this and be even better suited to contemporary transformations. The excited claims against normativity often rest on little reflected dichotomies such as objective/subjective, rational/irrational, descriptive/normative and so on. Sayer deconstructed these and convincingly argued that ‘values are within reason’, and they are within social reality. It has often been shown that there are values in reason; but it is also true, Sayer argues, that there is reason in values. Sociology is half blind if it neglects the normative character of social life and its potential to entwine with it. The key is to reflect on values, to observe them and to rationally argue for or against them, and to learn and modify them (Sayer, 2011). In my view, this is not about telling other people the ‘truth’ to which they need to adapt. It is about sharing the particular perspective as a sociologist and person, as an offer for collaboration and for co-experimentation that demands the researcher to learn and to adapt. What are the values that I argued for in setting up the FabLab and also in analysing this process in this text?

First of all, I am inspired by utopian thought and practice. There is a long tradition of utopian writing in social theory and philosophy (Wright, 2010; Levitas, 2005; Marx and Engels, 2002; Bloch, 1995; Bauman, 1976). This was brought to a new level in the work of Ernst Bloch (1995), who argued that utopia is not simply to be found in literary dreams of seemingly perfect worlds, but that utopia in the form of ‘concrete utopia’ is a central force in human history. It is practised whenever and wherever people strive to improve societal and human conditions[8], and their desires and anticipations are mediated with present possibilities and what is and what is not yet[9] are entwined in a process of becoming. He argued that such concrete utopias are experimental processes, which can neither ground themselves in ‘universal truths’ of the past or present, nor sketch out blueprints for the future. Trying to help a better world emerge is a creative process that combines imagination and practice. The people who engage in concrete utopias try to give them a certain direction and hope for positive results, but experiments are indeterminate processes and might turn out differently than expected. Learning from the process is therefore absolutely central. Although it is worthwhile for sociology to describe and analyse utopian practices, utopia is also an attitude towards the world (Levitas, 2005): inspired particularly by Bloch, I see the world as a process of becoming; contingent, yet also full of possibilities; partly changeable through human and individual agency, which is always within emergent processes that enable and constrain it. To me action research is a way to create new ways of

[8] What constitutes an improvement is something to be determined in process. According to Bloch’s process ontology, desires, dreams and humans can become different, there are no timeless universals of the ‘good society’. Although in Bloch’s Marxist philosophy the good society was a classless society, he did not sketch out how such a society would look; this would have been making up an ‘abstract utopia’.

[9] This is a key term in Bloch’s process ontology. The world is full of that which is not yet, a world of becoming, full of potentials, latencies and tendencies.

knowing personally and socially, a way to engage in this world of becoming, and to help spread a sense of possibility for change.

Second, as discussed in the chapter on TechKnowledgies, technology is an important aspect in human becoming and its novelty and change should be fostered. However, we need to pluralise 'technology' and ask which technologies can improve and foster human flourishing: not every becoming of technology is desirable. Such evaluations of different technologies are central in technology assessment, the field that I have been working in during this research[10].

Third, since technology is a form of power, democratising it is one aspect in the ongoing project of democracy. Although there are many models for what such democratisation of technology could look like, for example, through public debates, I think that one particularly important aspect is the inclusion of different people into processes of technical becoming. This does not mean that everyone should be included in everything, as some claims for more democracy in different areas, also concerning online communities, have it[11]. But an increased inclusion of different people in the arrangements that decide upon and enable the design and production of technology would be part of democratising these.

Putting into more concrete terms and partly answering why I am interested in open digital fabrication and FabLabs and why I chose action research as a method: being a utopian I think that social change through open-source practices and within them is possible, especially since we live in times of massive digitisations. Particularly, these practices challenge established arrangements of the development and production of technology through providing a prototypical way of creating technology differently. Particularly social scientists could offer reflexivity for these ongoing processes of organising technology and knowledge.

Being action researcher in the already normative fields of social transformation processes, such as starting a FabLab, is a messy process, as messy as social reality itself (cf. Brydon-Miller et al., 2003). Joy and anger, excitement and disappointment, rational debate and emotional upheaval were all part of what I experienced through doing this kind of research. From a classic understanding of value-free, 'objective' science this may sound terrible. But doing action research actually brings the researcher into extensive contact with the social field one is researching, with its fine details and ups and downs. Although action and research are tightly entwined in this process, they are not the same. Times of intense action in the field alternated with times of reflection at my desk and in discussion with my scientific colleagues. And this is how action research is supposed to be: action, reflection and research should inform each other and not simply form an indistinguishable knot. This is also a matter of time.

My involvement in the social process was strongest during the first one and a half years of FabLab Karlsruhe (summer 2013 until the beginning of 2015), also the phase where I gathered most of my empirical material from FabLab Karlsruhe through participant observation and autoethnographic analyses of my own actions and their consequences. After that, I reduced my involvement in the organisation of the lab, but stayed in contact. Analysing and writing about this process took place afterwards and involved working papers and presentations, which I discussed with colleagues and peers. Intersubjective validation, key for scientific quality especially in all forms of qualitative research, is equally possible in action research. I must admit, however, that action fell a little short from 2015 onwards. Analysing the case with some distance from the field was important to me and other tasks, projects and events at work also wanted attention.

[10] I have been working at the Institute for Technology Assessment and Systems Analysis (ITAS), an interdisciplinary institute of Karlsruhe Institute of Technology, Germany. See Grunwald (2009) for a general introduction into technology assessment.

[11] Pickering (2014), drawing on cybernetics to criticise naive ideas about democracy, shows the ontological improbability of reaching consensus or even debating with each other in larger groups of people if everyone is supposed to talk and debate with everyone. He offers an organisational alternative which splits these groups into smaller elements and places intermediaries and feedback mechanisms into the process of debate.

Furthermore, the organisation of the FabLab stabilised with people taking formal and informal roles and, thus, also gaining power. While I particularly influenced the founding process, also with my expertise as sociologist, the cycles of action, reflection and research ended afterwards. At the time of writing, however, a workshop is planned including the presentation of key insights of my PhD and a collaborative strategic planning for the near future of the lab.

Action research poses special requirements on an ethical conduct of research and on the management of the empirical material. Right from the beginning of the FabLab process I made my role as action researcher transparent to the others. Furthermore, I wrote a commitment that I shared with the FabLab group that I would only use empirical information in an anonymous way and that I aim at making my results public. I also invited the FabLab members to my annual presentations of the PhD and was very pleased that some took up my invitation. Also, chats in the lab have been opportunities to talk about my research, and of course to learn from the others about FabLabs. Besides such considerations, being an action researcher involved doing all kinds of things for or in the FabLab itself: being at and contributing to meetings, mailing, organising, presenting our FabLab concept to the municipality, writing research proposals including the FabLab, contributing to the website that was set up, discussing the statutes of the association, being talked to, debating and argueing with others, cleaning the room, building machines, showing the lab to guests, socialising with people in the lab and so on. All of this is part of the empirical material that I have gathered. Another part and very important to compare insights from Karlsruhe to the global FabLab movement were visits to other FabLabs and the many forms of content shared online by FabLabs or by organisations involved in FabLabs. There is also a growing amount of literature and research on FabLabs, which is a central secondary source of empirical data. Crucial for my empirical work was my research diary, in which I wrote observations, field notes and initial interpretations. This diary proved crucial in structuring the amount and diversity of my empirical material. The first entries deal with the emergence of the idea of starting a FabLab, to which I turn now.

4.3.2 Spreading desire

In the following, I show how several relationships emerged and engendered the collective desire and vision to start a FabLab in Karlsruhe and how becoming action researcher was involved in this. I first encountered FabLabs on Wikipedia, on the encyclopedia's page for 3D printing, in 2012. In search of a topic for my PhD, I read the writings of André Gorz (2010b) and Frithjof Bergmann (Bergmann and Friedland, 2007), two leftist philosophers who promoted 3D printing as a technology for local and non-alienated high-tech production. Already in 2004 Bergmann had written about high-tech workshops using 3D printers to transform the production and consumption of goods. Gershenfeld, thus, was not the only one to think about digital fabrication and how it might be used in novel ways. And searching for 3D printing online pointed me to FabLabs. What I could get from Wikipedia and some FabLab websites resonated with a vision sketched out by Gorz in 2007 – and I doubt that he was familiar with FabLabs – which intrigued me a lot:

> 'Existing tools or tools currently in development, which are generally comparable to computer peripherals, point towards a future in which it will be possible to produce practically all that is necessary and desirable in cooperative or communal workshops; in which it will be possible to combine productive activities with learning and teaching, with experimentation and research, with the creation of new tastes, flavors and materials, and with the invention of new forms and techniques of agriculture, building, and medicine, etc. Communal self-providing workshops will be globally interconnected, will be able to exchange or share their experiences, inventions, ideas, and discoveries. Work will be a producer of culture, and self-providing will be a way to self-fulfillment. […] I do not say that these radical transformations will come about. I am simply saying that, for the first time, we can wish them to come about.

> The means exist, as well as the people who are methodically working towards their realization' (Gorz, 2010b, pp. 12–13).

Gorz's vision to me gained particular strength in the light of his brilliant early analysis of the tensions of knowledge (which thrives if it is common) and exchange value (which needs scarcity) in contemporary capitalism and of open source as an alternative economic paradigm. Within a few days of encountering 3D printing and FabLabs online, my PhD topic was set. This I wanted to investigate and contribute to.

In winter 2012 and spring 2013, a media hype about 3D printing and the maker movement was clearly visible in Germany (e.g. Hollmer, 2013; Otto, 2013). This was also noticed by some of my colleagues at the Institute of Technology Assessment and Systems Analysis (ITAS), where I was working on my PhD, and talks about my PhD tended to move towards the more general potentials of 'making' and 3D printing as seen and speculated by my colleagues. Spring 2013 was also the time when the ITAS project 'Quartier Zukunft – Labor Stadt' (www.quartierzukunft.de, engl. 'District Future – Urban Lab') was in its early phase and looked for interesting projects in the city of Karlsruhe to collaborate with. Quartier Zukunft is a transdisciplinary project with the long-term goal to transform a district of Karlsruhe towards sustainability. It is cooperating with the municipality, KIT, business and civil urban society. I was not formally involved in the project, but when I explained my PhD topic to a colleague in this project and briefly turned to FabLabs, he readily suggested that a FabLab might fit well in Quartier Zukunft. Besides such motivation by colleagues I knew of a mailing list (of 16 people by that time) at KIT about 3D printing and FabLabs. I was at a talk about 3D printing by one key person of this group – who would also become strongly involved in the FabLab. And a visit to Karlsruhe's Chaos Computer Club showed me that there is an active hacker scene but rather closely related to software (for a genealogy of 'hackerspaces': maxigas, 2012). Taken together, these things affected me, and I thought there is potential for a FabLab in Karlsruhe and maybe even growing interest.

I present these initial times that turned me into a 'visioneer' in some detail since I want to emphasise something which is important for FabLabs. Desiring these experiments is not about making up plans in the 'mind' and then realising them. Rather, as Ingold puts it, to 'imagine [...] is not so much to conjure up images of a reality "out there", whether virtual or actual, true or false, as to participate from within, through perception and action, in the very becoming of things' (Ingold, 2012, p. 3). Imagination and desire is a distributed and emergent result of collective assemblages together with which it is being formed. In my own case this initial collective machine in Karlsruhe can be traced back to these early experiences.

Inspired and motivated by these signs and encouraged by my PhD supervisors, I saw the situation I was involved in as an opportunity for an engaged and inventive form of transdisciplinary research. I, therefore, made the decision in June 2013 to send an email inviting people to join the process of creating a FabLab in Karlsruhe. The initial recipients were the above-mentioned 3D printing mailing list, the Chaos Computer Club, the students of a design school in Karlsruhe and a student group interested in 3D printing that I was pointed to. The email read that it was planned to establish a FabLab in Karlsruhe as a project within Quartier Zukunft and that everyone is welcome to join the process. Within three days more than 20 people replied, many familiar with FabLabs and 3D printing, and showed their interest, such that I soon started to organise a first meeting and to find a date for it – all via email. A month later, around 30 people gathered in the seminar room of ITAS. Amongst them many people who had emailed me, many who had not but had heard of it somewhere else and two colleagues from Quartier Zukunft. This exciting evening included introductions of the people and their interests, an introduction to Quartier Zukunft, questions about what FabLabs actually are and sometimes heated debates of what to do first and how fast. It ended with arranging a second meeting and adding the words 'FabLab Karlsruhe' with the label 'planned' to the wiki of the global FabLab movement, hosted by FabLab Ísland as a community service, for which I had registered before (http://wiki.fablab.is/wiki/Portal:Labs, accessed 03.03.2015). This concluding action was the first act of imitation that explicitly linked Karlsruhe into the global experiment. About 150 other FabLabs had already written an entry and made themselves visible. The FabLab map using this wiki as data source from then on showed MIT's FabLab logo above Karlsruhe. From then onwards, a slightly changing group of about 15 people met every fortnight at ITAS to establish FabLab Karlsruhe. There was some fluctuation in the group with some people dropping out and others joining the process. Most core members of this group have remained active in the lab to the day of writing.

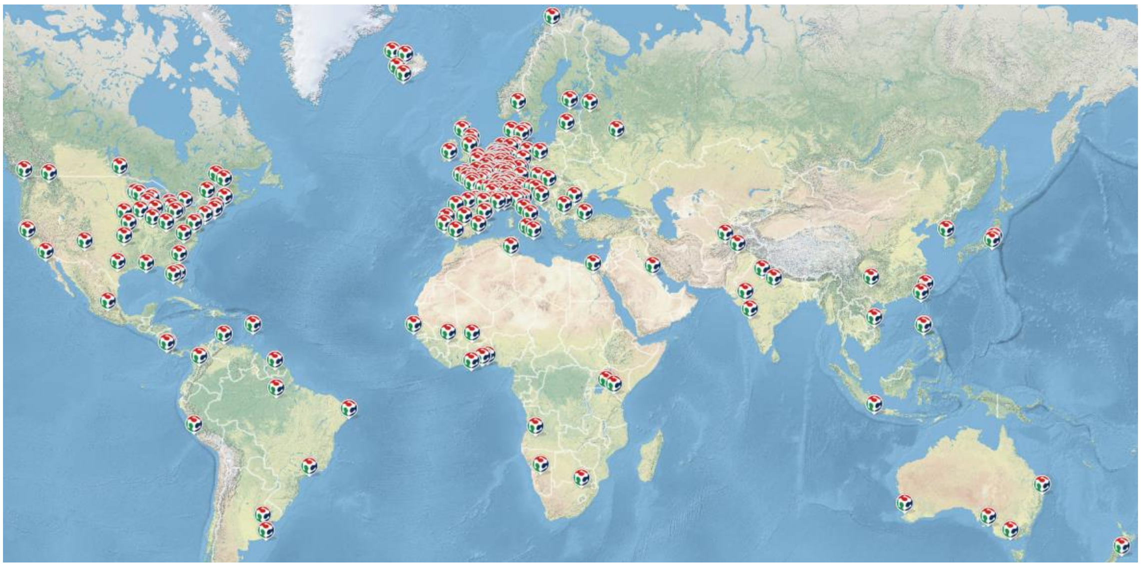

Figure 4.1: World map of FabLabs 2013 (http://wiki.fablab.is/wiki/Portal:Labs, accessed 04.03.2013)

Next I turn towards the formation of a collective machine that mobilised and stabilised FabLab Karlsruhe on a particular trajectory that was unfolded by the group. Within the different elements of this machine – collaborations with research, 3D printing, and a particular form of citizenship that I analyse in more detail – the experimental imitations that took place point to wider patterns in grassroots FabLabs.

FabLab Karlsruhe's initial host institution was the university, KIT. Above I showed how FabLabs came into existence at MIT due to technoscientific cultures and wider cultural practices. Even though MIT still is an important element in the collective machine of FabLabs, other research institutions and practices of research have taken part in it. Two of Europe's oldest, largest and most visible FabLabs have close connections to research. FabLab Amsterdam is run by the Dutch 'Waag Society', which investigates new media and emerging technologies to foster cultural and social innovation (www.waag.org, accessed 10.04.2015). FabLab Barcelona was founded by the 'Institute for Advanced Architecture of Catalonia' (www.iaac.net, accessed 10.04.2015). When I talked to colleagues at ITAS, it was often pointed out that since FabLabs have close links to MIT it would fit to KIT as well (indeed, the name is no coincidence). Quartier Zukunft has been conducting its much larger real-life experiment with FabLab as one element. The FabLab in this case was seen as suitable in a transdisciplinary research project. In a way, MIT's outreach programme, which motivated the initial FabLabs, was also a transdisciplinary project. Thus, whether it is giving students access to the FabLab or creating links to the public, some FabLabs serve to reconfigure science and science and society relations. Furthermore, strong examples of such FabLab and research ties emphasise the importance of knowledge production and knowledge-sharing, which are key principles of science and research. This could give some cultural and economic protection to the experimentation in FabLabs without putting profit first as in business-oriented technological settings.

One of the main producers of the FabLab Karlsruhe community and of many other FabLab collectives is the machinic assemblage of open-source 3D printing. Many of the key persons who were part of establishing FabLab Karlsruhe came to FabLabs via open-source 3D printing. Having built such machines themselves or wanting to build or to access one, they had become familiar with FabLabs and had the wish to share their 'hobby' with each other and/or to make the technology available to others. Most of them enjoyed tinkering and DIY practices and 'hacking', and many would agree to being 'makers'. FabLabs and open-source 3D printing assembled with each other and have since been on a trajectory of 'co-becoming'. In the initial FabLab model there was no 3D printing, but a few years later 3D printing came to define the core of many FabLabs, including FabLab Karlsruhe. Below I analyse, however, that there is much more to FabLabs apart from 3D printing.

'FabLab Karlsruhe': this name was not a coincidence, rather it adopted the general pattern of name-giving of FabLabs which is 'FabLab *name of city*'. There are some exceptions but they only confirm the rule (see: http://wiki.fablab.is/wiki/Portal:Labs and www.fablabs.io, accessed 10.04.2015). Most FabLabs are in cities and not in rural areas. Cities are key to modernity, which has been especially strongly experienced in processes of urbanisation (classic: Berman, 2010). Cities are condensed places of flow, exchange, encounter, difference, conflict, interaction and innovation and, therefore, offer much potential for creativity. They provide a fruitful milieu for FabLabs, and if only that there are large numbers of people in one place, such that there are enough who are interested in participating in FabLabs. There is a strong sense of place as FabLabs entwine 'online' and 'offline' interactions, technologies and cultures and as a result are strongly localised. And the local circumstances in Karlsruhe would come to play an important role.

There is a second, more political sense that links FabLabs and cities: the 'citizen' aspect[12]. From antiquity onwards, the city has also been a political entity with those participating in politics being the citizens (Eßbach, 2011). During history the politics of these citizens has taken many different forms, yet also involved self-organisation and the creation and maintenance of commons (Harvey, 2012). Recently, Hardt and Negri emphatically announced that 'the metropolis is to the multitude what the factory was to the industrial working class' (Hardt and Negri, 2009, p. 250, italics omitted). In their political theory the commons play a key role in enabling and creating new forms of subjectivity and sociality of a multitude in becoming that should learn to self-organise life beyond 'market' or 'state'. Whether or not people in FabLabs share the political aspirations of the two neo-Marxist authors, many FabLabs are and explicitly present themselves as community-based workshops; as organisations run by citizens for citizens and, therefore, as 'political' organisations fostering and experimenting with self-organised technosocial arrangements. The political sense of FabLabs was clearly felt during the first meeting when the gathering of some researchers and about 30 'citizens' showed the will and the commitment to together launch a FabLab.

In addition to such enactments of general political categories, there was a very German way in which FabLab Karlsruhe began to take shape from the kick-off meeting onwards. It became a 'Verein', a voluntary, member-based organisation, the most common legal form for civil society organisations in Germany (Zimmer et al., 2004). In the second meeting, there was a vote concerning what legal form the FabLab should get. And although three people opted for the FabLab to become a company, in which they would also invest their money, the majority voted for it to become a Verein. This vote was accompanied by a short debate, in which arguments for a quicker and more efficient start of the lab as company were outweighed by arguments for a collective governance and a less risky start of the lab as Verein. Furthermore, many people who took an active part in the founding group of the FabLab were involved in other such associations and strongly in favour of this organisational form – as were most other German FabLabs at that time.

[12] This aspect is also emphasised in discourse on 'citizen science' (see Dickel and Franzen, 2016).

What followed that decision were about six months of continued debate about whether our FabLab should be in the economic or non-profit sphere of society, now however, with the German state. This meant writing a statute of the future association that would regulate the internal governance, e.g. how many people get elected to lead the association for 12 months, how do you become a member, what are the goals of the organisation etc. But it should also make the purpose of the Verein clear to the bureaucrats who, based on this document, decide whether it is a non-profit, aiming for socially beneficial services, with tax-exempt status or a for-profit association. And although there are clear legal rules for these texts and different statutes of other FabLabs were imitated, this process proved to be very intense and time-consuming. It remained the most prominent task in the months when the FabLab mainly consisted of a group meeting every second week in a seminar room to plan a FabLab. It took much time and effort to explain the non-profit goals to the bureaucrats and to carefully craft the text for this purpose. What the state officials found difficult to understand initially was that the FabLab was planned to be an accessible workshop that used novel machinery to facilitate the production of things but was not aiming to make a profit[13].

The associations called Vereine are the most typical form of organising civil society and civic engagement in Germany and the FabLab shared in this sphere, which has its roots in the 19th century. Due to the highly restrictive political regimes in the 19th and early 20th century, Vereine became a popular way of organising particular interest groups outside the institutionalised political sphere. This however led to a pillarisation and politicised many of these organisations – even doing sports used to be a political act. The state reacted by strongly regulating them. Nowadays, based on 19th-century laws the state still decides upon which association is socially beneficial and, therefore, exempt from taxation, for example (Zimmer et al., 2004). Concerning internal governance, however, this is a flexible organisational form, which leaves room for the members to design their organisation, although this design process again is highly regulated and demands particular documents, minutes and rules to be followed if one does not want to break the laws. Debates about these rules and about how to proceed with internal governance have been an integral part of organising the FabLab from the beginning onwards, whenever its ‘official’ status was concerned. And before the Verein was established in February 2014 through 27 signatories, the FabLab was not a legal body and could not officially act in the common interest, e.g. rent a room. This shows how national cultures and organisational styles leave their mark on FabLabs – in Karlsruhe particular facets of German civil society were imitated – yet it also emphasises the organised production of citizenship.

Civil society, although often used to designate positive forms of social organisation, is enacted in highly heterogeneous and contested ways. ‘Civil society is a key institutional domain for the transformation of meanings, the creation and hybridization of projects, the practice of individual and collective agency, and the contested production of frames and discourses’ (Walby, 2009, p. 218). In civil society struggles are fought for the future of society and organisations such as the FabLab are ways to stabilise particular meanings and projects and to organise particular forms of citizenship. Consequently, FabLab Karlsruhe has always been about more than the desire for digital machines. It has always also been about creating and stabilising a form of citizenship and citizen that centres around the collective agency concerning these machines. Smith discusses how such a FabLab version of citizenship has been highly contested in Spanish and Brazilian projects that tried to use FabLabs for empowerment in poorer neighbourhoods where particular traditions and forms of life rejected the labs (Smith, 2015). FabLabs, one could say, are a form of politics by means of machines and their organisation. Importantly, this form of citizenship differs from the modern imaginary of citizenship that is based on participation in public debates. From the ancient agora to mass demonstrations, parties and parliaments, the modern citizen is typically framed and enacted as the one

[13] Below in the chapter on the experimental economy of FabLabs I analyse the unclear relations of FabLabs to the economy.

who speaks[14]. Especially citizen run FabLabs enact a citizen who does not only speak but organises and produces technology.

In the following parts I change the mode of analysis to bring into view the plural dimensions of experimentation in and with the lab. The dimensions I selected for the analysis concern the creation of experimental agents (individual and collective) and how they intervene in different forms into the realities in Karlsruhe and beyond. All of the dimensions are furthermore justified through linking experimentation in Karlsruhe to experimentation beyond Karlsruhe at other sites of the collective machine of FabLabs. Through this, the analysis points to patterns in FabLabs that provided the ground for imitations in Karlsruhe, yet also shared problems that are faced by other FabLabs as well. The first dimension is the constitution of the group, and experimental interventions to form and transform its collective identity and its agency as a collective experimenter. This is a fundamental aspect, since there would be no experiment without an experimenting actor. Second, the analysis turns towards practices of visioneering within and with the FabLab that experiment with the imagined spaces of possibility of the lab and create desires to change it. Third, it is shown how practices of repair and maintenance are crucial to sustain experimentation. And fourth, the role of experimentation with different economic relations is shown. This discusses how ‘openness’, commons and material and financial constraints and interests are creating experimental tensions. Together these dimensions show how the TechKnowledgy of open digital fabrication is being experimentally unfolded in Karlsruhe and how this relates to the collective machine beyond this individual lab. The analysis will show how people actively position themselves and others within the experimental collective machine and how there is social, organisational and individual learning in consequence.

4.3.3 An experimental group

Imagine that a sociologist intends to start a metal-working workshop with the aim to provide additional education for pupils in welding and manufacturing with steel, such that the pupils have better chances of getting good jobs in heavy industry. To me this sounds absurd, yet I have started a FabLab. Using a welder or a 3D printer is probably comparably difficult, and when I started the lab I did not know how to use any of these. I still do not know how to operate a 3D printer – I have now however built and operated a laser cutter in the FabLab. Actually, no one wanted to know whether I could use a 3D printer before they joined in the FabLab process. For about 30 people who came to the kick-off meeting hosted by a sociologist in the interdisciplinary Institute for Technology Assessment and Systems Analysis this seemed perfectly fine. Amongst these were people that knew very well how to operate 3D printers but also people interested in other aspects of a FabLab. Especially for grassroots FabLabs the group that organises and forms the lab is central since these operate based on voluntary involvement. In this chapter I address how the formation of the Karlsruhe group was realised and contested, and how the group dynamics entailed experimentation with the group itself. Many of these dynamics are influenced by processes beyond the lab and imitate larger constellations that have been important in socially defining FabLabs in general.

Above I have already discussed how an ethos of openness has spread across networked cultures and become a political desire. In the following, I show how openness has to be considered a dynamic and unfolding ethos which contributes to experimentation in FabLabs and is practised and contested in relation to people, objects and organisations. It is not solely a practitioner’s description of how the world is seen but it equally affords imaginations and struggles over how the world could and should be. How is openness being experimented with in and through FabLabs? I answer this question three different ways with an analysis of a discourse of inclusion and its effects in organising FabLab Karlsruhe, the formation of an organisational maker identity and a third part on the role of digital objects in shaping the sociality of the lab. An ethos of

[14] The work of Habermas can be seen as a scholarly manifesto for this form of the debating citizen (Habermas, 1991).

openness is particularly important in all of these dimensions to motivate experimentation, yet it is also shaped into a particular configuration through the outcomes of the interventions.

Inclusion!

During the first weeks of FabLab Karlsruhe discussing and writing the 'manifesto' that would be used to describe the aims of the organisation was particularly important for explicitly addressing the group and forming a vision of the organisation. The idea was to have this manifesto for an internal and external definition of what the FabLab in Karlsruhe stands for and aims at. It was a text defined by the initial group but also included aspirations for what the group should look like in the future. The first weeks were also defined by a certain fluctuation in the group. Whereas about ten people formed the core and regularly attended the meetings, various others came by once or twice. Introducing each other was, therefore, being done over and over. The identity of the FabLab became strongly linked to the identity of the people attending the meetings. Accordingly, as one of the first steps to come to a manifesto it was suggested to conduct a survey amongst the people listed on the newly created mailing list that asked the group 'Who are we?' and 'What do we want?'. This survey listed subjectivities such as 'tinkerer', 'artist' and 'scientist' and aims such as 'use machines for my projects' or 'contribute to sustainability', but actually it did not result in a clear winner in any of these items. Everything achieved similar levels of clicks. And although this might suggest that the group had already reached a consensus regarding their goals, this was not the case. In the first two meetings, it was passionately discussed what the most important thing about FabLabs was and how to get there. Drawing on this survey, a small group including me started to draft a text for the manifesto. The headlines for the paragraphs of this short text read 'technology for everyone', 'open source', 'diversity, cooperation, equality', 'education', 'creativity, experiment, innovation' and 'sustainability'. This draft was then collectively discussed but not drastically changed or contested and all the different paragraphs were accepted.

There was, however, a struggle over one paragraph that pointed towards an important aspect in FabLab culture. Initially the draft read that work and knowledge in the FabLab supports open source and the sharing of knowledge. A minority in the FabLab group with aspirations for using the FabLab commercially to support their self-employed work argued that this is too restrictive and would prevent small companies or self-employed people from joining and using the lab. In the end they won the argument. We then added to the paragraph that the FabLab pursues the open-source approach but that everybody can decide individually how much of one's knowledge they share. A couple of weeks later someone from another German FabLab emailed and argued that this would make the idea of open source ineffective and, thus, equally took the either-or perspective that was read into the first draft by the commercial minority.

Yet in Karlsruhe the group made a similar move that MIT made as well a year before. In 2007, the group around Gershenfeld after intense discussion published the 'Fab Charter' to encourage the following of these guidelines in the growing number of FabLabs. In 2012, a new version of this charter was published by Gershenfeld which amongst other changes had a small but important shift in its idea about intellectual property in FabLabs. The 2007 version read that 'designs and processes developed in fab labs must remain available for individual use although intellectual property can be protected however you choose'. In 2012, the possibility of protection was emphasised more strongly: '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' (http://wiki.fablab.is/wiki/New_Fab_Charter, accessed November 2016). The wording changed from 'must' to 'should remain available'. Other changes in the new charter similarly moved from a restrictive to a more encouraging tone. Gershenfeld rewrote the charter also because of pressure from labs that wanted to attract and foster commercial activities (Peter Troxler, personal communication). Furthermore, by 2012 many open-source hardware companies were actually running and have similarly been negotiating the meanings of open source and their relation to commercial activities.

Although this is an instructive episode on the contemporary contentions of intellectual property it is equally instructive about the ways in which rules and goals are being handled in FabLab culture. The Karlsruhe manifesto actually settled the dispute about the goal of the FabLab by shifting towards multiple goals that the FabLab aspires to. And importantly, these were not seen by the group as necessarily dependent upon each other. The consensus that had been reached was based on the idea that the goals 'can' and do not 'have to be' followed, as explicated in the struggle about the wording of the open-source paragraph. Similar tendencies of such containment of goals besides access to technologies have been observed in open-source software projects, where the focus lies on the production software and not on the ends towards which this software might be used (Coleman, 2012). Similarly, although the Karlsruhe manifesto on its web page gives a link to the Fab charter and manifesto and charter are shown in the lab, to my knowledge they have not been used so far in Karlsruhe to prevent or enforce something. This does not mean that they are irrelevant, however. They are the vehicles for a 'soft' form of governance based on discourse which operates through information and encouragement rather than through enforcement. In the case of MIT this is especially evident. Although initially formal relations to the first labs were established, the 'movement' is now too large and diverse for the MIT to have any formal control.

Therefore, whether the manifesto for FabLab Karlsruhe or the Fab charter, these are discursive imitations of a rather liberal and tolerant culture, one that tries to include rather than exclude. Such inclusion, however, is based on the ideas of access to and sharing of machines and knowledge, which in their entanglement are dependent upon a collective that provides the common resources of machines and knowledge. This already is a very strong goal that many FabLabs at least discursively pursue. Such discourse can be seen in an instrumental manner since the common pool of economic and knowledge resources grows together with the number of people that engage in FabLabs. In Karlsruhe it was important to draw in many people to actually have enough members paying and contributing to build and sustain the lab. Inclusion, however, is not solely an instrument but also a value in itself that is being enacted on this discursive level. The first paragraph in the Karlsruhe manifesto reads 'technology for everyone', and the Fab Charter speaks about 'access to tools' right at its beginning. Despite being resources for the labs, individuals are addressed as being able to use the labs as tools towards their empowerment. Openness in FabLab discourse is, therefore, primarily framed as 'open access' and considerations what such access may be used for come second. However, the manifesto and the Fab charter also speak about sharing and a community that constitute FabLabs and place individual access in the context of access to a common resource to which such access contributes to or shall contribute to. In Karlsruhe, this is expressed, for example, through the aims of 'co-operation' or 'education'. FabLabs promote a sort of collective individualism, which addresses individuals with potentially diverse goals that are nonetheless part and enabler of a commons that in turn enables their individual actions. The aspired inclusion of people in this commons, e.g. FabLab Karlsruhe, is conditional upon the individual contribution to the commons. Such combinations of individual and collective concern have been found in other areas where the ethos of openness is evoked (Tkacz, 2015; Coleman, 2012). Openness is always relative and it relates at least two entities; already in discourse.

Beyond discourse, however, there is also practice. And the widened expectations of inclusion crucial for FabLab discourse are also faced with exclusive practices. Actually, exclusion is crucial for collective activities and the sustaining of common resources (Williams and Hall, 2015; Bollier and Helfrich, 2012). In the following I analyse how the relations of inclusion and exclusion have been actively addressed and contested in the FabLab and show how the tensions that arise here are the stuff of experimentation. Openness, inclusion and exclusion concern the experimental constellations of different elements in a FabLab.

Becoming makers

The recent years have seen a growing interest in the 'maker movement' with which many members of the Karlsruhe FabLab would also identify. However, such an identification of persons and the organisation with this 'movement' did not necessarily precede the establishment of the lab. In the following I analyse how particular interventions were made to create a local form of a ‘maker’ organisation with a particular appeal. FabLab Karlsruhe can on this level be considered to be an imitation in a larger process of cultural change in which digital fabrication and hacking practices are moving, as Troxler puts it, ‘beyond consenting nerds’ (Troxler, 2015). Above I noted how on a global discursive level this move started in 2005 when the term ‘maker’ was introduced by a publisher, to add to and partly replace the sometimes negatively connoted term ‘hacker’ and to address a larger audience. In such a spirit the Karlsruhe manifesto states that ‘everything people might be interested in should be possible in the FabLab’. Similarly, this widening has been propelled by the thousands of novel makerspaces, FabLabs and novel hackerspaces beyond software across the globe that reach out to include more diverse technologies and more diverse audiences into experiments with sharing and creating technology, forming the ‘maker movement’. Semantically drawing on this, the website of FabLab Karlsruhe, in 2016, presents the lab as ‘the heart of the local maker scene’. The FabLab has been defining and influencing this scene locally, and experimental efforts to bring such a scene into being have taken place.

A particularly relevant field of experimentation has been the definition of the group itself and efforts to reach out to people. Most of the members of FabLab Karlsruhe practice particularly strong relations to digital technology and they are mostly well-educated white men between 20 and 40, often with a professional background in technology. In short, they are close to the typical male-dominated technological cultures in hobby tinkering or in hacking. Karlsruhe is nothing special here, but rather it expresses the general trend in FabLabs and the wider maker movement which has often been criticised for its lack of diversity (Hielscher et al., 2015a; Toupin, 2014; Walter-Herrmann and Büching, 2013). This also reproduces dominant features of technological cultures and fields, which are mainly male and middle-class, and which have been criticised by feminist studies (e.g. Wajcman, 2007). Although the majority in FabLab Karlsruhe form a rather homogeneous group, this does not mean that diversity does not exist at all. There has been active experimentation with inclusion and recursive learning with dealing with a growing and increasingly diverse group.

In the initial meeting of the FabLab project, an important question being debated was the difference between a hackerspace, a makerspace and a FabLab. Indeed, beyond the name this difference is not so easy to tell. Of course, these have different genealogies and different points of reference, with hackerspaces being strongly rooted in the culture of software hacking. Yet, many practices, such as tinkering with micro-controllers, programming or even 3D printing are similar. Even in their self-descriptions these organisations partly overlap as places where people pursuing technical projects come together. And all of them experienced strong growth from around 2007 onwards (Hielscher et al., 2015b; Van Holm, 2014; maxigas, 2012). Indicative of how this growth mutually supported these organisations in terms of the attention is that some FabLabs even present themselves on the wiki for hackerspaces (https://wiki.hackerspaces.org/List_of_Hackerspaces, accessed 20.02.2016). FabLab Karlsruhe and some of its members have also been part of large hacker events organised by the German hacker association ‘Chaos Computer Club’. Therefore, instead of seeking differences in such general comparisons, differences have to be found in the situated histories of particular organisations. Then it might even be that FabLab y is more similar to hackerspace y than to FabLab x.

In Karlsruhe there were active contentions about the differences of these organisations. From the beginning onwards some members of the Karlsruhe hackerspace became part of the FabLab project. And these were not the only ones who felt that a FabLab offered different possibilities than their hackerspace. A middle-aged man said that he knew two hackerspaces, and although he would like to take his young daughter to a shared workshop with digital technologies, he would not take her there. They appeared to him as too confined in their social composition and too anarchic and messy in their organisation and their looks. One counter-argument was made that instead of reaching out to a diverse audience, it would be better to get only tinkerers and hackers together so that they could really advance their projects and share expensive tools.

The majority did not agree, and the person raising that argument dropped out of the process afterwards. The discussion even compared makerspaces and FabLabs; the former had also emerged a couple of years before to also host makers and digital machines. I intervened in the discussion and recounted some of the thoughts that made me pick FabLabs initially – my email to invite people into the project was already the result of my selection. I argued that FabLabs had a clearer concept with their focus on digital fabrication and networking amongst the labs with an emerging international organisation, as compared to makerspaces, which were also semantically closer to the more anarchic and informal style of hackerspaces. FabLabs seemed to me to have a more promising potential and could, therefore, also possibly attract more attention from others. No one disagreed. It is interesting, however, to note that after the FabLab had opened some members spoke about close-by hackerspaces or makerspaces and the people there as being similar and doing similar things as are done in FabLab Karlsruhe. Whilst not everyone agreed with that, it shows that working on the lab's identity and comparing and differentiating it from other organisations had not been confined to the initial weeks of the project.

Besides these individual preferences, at that time grassroots FabLabs were not as widely spread as nowadays. The online search results at that time – a little less so today – showed mainly FabLabs from the first wave before they went 'grassroots'. Labs with close links to MIT and institutional support, such as Europe's largest labs in Barcelona and Amsterdam, showed pictures and videos with more of an avant-garde instead of hacking feel to them on their well-designed websites. Links to such Internet resources about FabLabs were also circulated and indeed many in the Karlsruhe group had browsed the Internet to get to know about FabLabs. Indeed, besides the idea of sharing technology, aesthetic conceptions about how such sharing should look and feel played an important role in defining the FabLab at the beginning. Such aesthetics can be seen at work in the following image:

Figure 4.2: From left to right: logos of hackerspaces.org (http://wiki.hackerspaces.org, accessed July 2016), MIT FabLab (http://fab.cba.mit.edu/about/logos/, accessed July 2016), FabLab Karlsruhe.

Hackerspaces uses large pixels to give an old-school computer game look. MIT shows a three-dimensional cube and symbols for people. Karlsruhe's logo is based on a pyramid looked on from above (three-dimensional object, and a pyramid can be found on the main square in Karlsruhe). The pen represents creative work and learning, the wrench technology, the leaf sustainability, the speech balloon communication.

Besides crafting the statutes and manifesto, the first months in the planning phase also entailed designing the lab's appearance online and in printed documents. This entailed setting up a website, which in its layout was mainly created by two designers participating in the group and was technically set up by software programrs in the group. Texts were collaboratively written for the website, and pictures of technical projects (made at home by some, since there was no lab yet) that aimed to represent the lab were selected. Social media channels were set up, and it was carefully thought about what should be posted there. Furthermore, the logo was collaboratively created again with the designers taking the lead. Several different logos created by members were controversially discussed over a number of weeks. However, after much discussion on logos, the winning logo, which tried to take the manifesto into account, won the support of the majority immediately after it was shown. Logos and icons are particularly dense condensations of meaning. This one proved to be a successful imitation of MIT's 'official' FabLab logo and expressed the aesthetic appeal and the diversity of practices that the group imagined at that time.

The picture that was shown first on the FabLab's website and, thus, chosen to best represent the lab at that early stage was shot during a repair event where many of the FabLab group participated. It is the following picture:

Figure 4.3: Extract from the website of FabLab Karlsruhe in 2014 (www.fablab-karlsruhe.de, accessed February 2014). The text translates to 'everyone can participate!'

Similar to the picture Gershenfeld used to represent the Boston FabLab, the picture shows a group of people surrounding, watching and operating technical equipment. Amongst them, however, a young boy and a woman are meant to express diversity of the group. Not only online, but also after the lab had opened, such selections were made to represent the lab and to convey a particular story. Whether it was in talks to the municipality concerning possible spaces to let, during open days of the area where the lab had just opened, when the press visited or when interested visitors to the lab were introduced to FabLabs, a similar story has been told by many from the beginning onwards. The story is that the FabLab is a community that organises the sharing of digital fabrication technologies and that this community is diverse and inclusive or at least aspires to become so. For press visits different people, including children, and different technical projects were coordinated to be present in the lab. And in many explanations the exceptional people in the group were particularly emphasised, such that even though there were only two or three of them, the FabLab was said to have children and elderly people as members as well. In a nutshell, digital technology plus inclusion has been a central message that many in FabLab Karlsruhe have tried to convey. Such creation of a narrative is an important and actively designed intervention to reach out to a diverse audience and in turn attract more diverse people to manifest this narrative. But this does not only operate as text, its aesthetics stretch from pictures, the interior of a room or the clothes people wear (the FabLab had t-shirts for helpers during special events or trade fairs) to the people and their actions themselves. Aesthetics is an important part in every culture, yet it does not simply reside in cognitive evaluations or textual narratives. Aesthetics is enacted in spatial and relational atmospheres, involving the bodies of people (Böhme, 1993). The creation of an atmosphere of openness is thus more than the discourse of openness. It involves the arrangement of different elements that are aesthetically perceived and performed and this performance leads to a particular configuration of openness as perceived and enacted through relations.

It is often criticised that many projects that evoke ‘openness’, such as Wikipedia, propel a discourse of inclusion but have only limited diversity in their participants. And the same critique has been addressed at hackerspaces and FabLabs (e.g. Tkacz, 2015; Toupin, 2014). Mostly, however, such research sees the social as rather static and neglects the performative character of experimentation. Although there is still limited diversity in FabLab Karlsruhe, there have been efforts to include more diverse people starting with the representation and narrative of the lab. From this perspective these are conscious interventions of an experiment which is based on the question of how to attract more diverse people that in turn contribute practically to experimentation with digital technology and inclusion. And diverse people have actually been becoming part of the FabLab, although some, including me, still think that there is room for improvement here. A particularly important aspect that influences the composition of the group are the technical objects that are being used in the FabLab. Below I analyse how these co-constitute subjectivity and sociality and affect experimentation.

Objects and subjects

Maker identities are strongly linked to the objects that are being tinkered with by persons (Toombs et al., 2014) and the sociality is particularly formed around the objects of digital fabrication and the desires these engender. Above I discussed how 3D printing was a central motivation for the majority of people in the group to start the lab. And indeed, the FabLab concept is based on tools for digital fabrication. The social culture of FabLabs is strongly object-centred, and these objects are an important part of the sociality (cf. Knorr-Cetina, 1997). Relations amongst subjects and objects are not only narratively built but also practically. And thus, the objects have an impact on the group and the relations amongst people and, of course, people and objects. Even though there are many different objects and different relations, I focus on three objects and their co-productions of the group and its experiments: the wiki, used as a central tool for organization; a set of digital fabrication tools; and the room of the FabLab. All three of them enable and constrain particular practices, and all of them have relations beyond Karlsruhe that are important for experimentation and imitation. FabLabs do not equally value all skills but foster experimentation with technosocial environments that enable particular becomings of people, technologies and socialities and not others. I analyse these in relation to the three selected objects.

The wiki has been an integral part of the process of organising the FabLab from the initial meeting onwards. Wikis, Internet platforms that can be collaboratively edited and viewed by their users, have been important technologies to circulate knowledge in software and Internet cultures from the 1970s onwards, with many different versions nowadays being downloadable and usable for free (for an instructive overview see https://en.wikipedia.org/wiki/Wiki, accessed November 2016). They are iconic technical objects and organisational forms for ‘open’ knowledge (cf. Tkacz, 2015). When it was suggested in the first meeting to set up a wiki so that the group could collect and share knowledge and organise itself there was hardly a discussion. For most it was self-evident that a wiki would be a suitable tool to support the organisation in addition to the biweekly meetings. Different working groups were established, such as concerning the search for locations in Karlsruhe, and each created their wiki page. The topics for the coming meetings were collected on a wiki page and minutes of the meetings published. After the lab had opened its doors the wiki still retained its important role in organising. Rules for the lab were suggested and discussed there, projects were documented, courses offered and interest in them shown, for example. Most of its content being viewable without restrictions when steering a web browser to its address, the wiki also became a tool to exchange knowledge with other FabLabs. Interested people, often from other FabLabs, were pointed at the wiki for information on which machines and materials were available or for a particular solution to a problem that was documented on the wiki. Equally, some other FabLabs have publicly accessible wikis and a wiki for the whole FabLab movement exists where much information about FabLabs in general can be found and where individual labs can document their existence.

Wikis, although they are framed as providing open knowledge, are often not that easy to use. The wiki chosen in Karlsruhe had a basic functionality but required the use of a particular syntax to edit and to format pages. While many of the wiki advocates were already familiar with the system, others raised their concerns after the wiki came into use. These concerns such that it was difficult to understand the wiki's structure and to edit its pages were often replied to by offering help to use the wiki. The wiki itself even offers a 'play-ground' page to try its functions and learn to use it without changing its contents. And although many understood that the wiki is not that straightforward to use for some people, the usage of the wiki was never questioned. The wiki, therefore, exemplifies a central feature of openness and the sociality in FabLabs. Sociality and knowledge are mediated by technologies. There are particular technologies, however, that have a tight correspondence of subjects and objects and entwined with these a particular group in the lab sets the tone and style for the knowledge practices. Although such knowledge is in principle accessible to everyone, you have to know or to learn how to access it and how to produce and document it. This means you have to adapt to particular practices important for the majority in labs. Sharing is, thus, dependent upon particular skills to share. No one would stop you from acquiring these, but the skills themselves and the technical object that they correspond with are set. This is evident with digital fabrication technologies.

Digital fabrication machines have been the defining feature of FabLabs from the initial experiments at MIT onwards, where technoscientific visions of machines that make machines drove and legitimated research. The first FabLabs were set up to see what people would do with digital 'personal fabricators'. And when the lab network grew, MIT published a list of suggested machines that would define a FabLab, which has been extended over the years with FabLabs becoming more diverse. And as I showed above, the practices and imaginations of open-source 3D printing have attracted many to FabLabs. Furthermore, the imaginary of the FabLab network is fundamentally tied to the ontologies of information, knowledge, digitisation and materiality that these machines and their arrangements in processes in FabLabs afford. A key idea is that every FabLab should have a similar technosocial infrastructure to facilitate similar processes of digital fabrication and networking. In this imaginary, networking and knowledge-sharing via the Internet should become relatively easy since FabLabs could easily translate digital information into the material world – although in practice such networking is not as straightforward.

When the FabLab had opened, it quickly filled with rather old computer numerically controlled (CNC) machines that members brought into the lab either from their cellars or from companies that did not need them anymore: printers and plotters to print on paper and small laser plotters to create electric circuitry with an optical process. There were plans to build a cutter from one of the print plotters to actually cut paper instead of having the machine draw on it. Of course, there were 3D printers as well, and half a year later a large open-source laser cutter (see Lasersaur case study) was built and now presents the largest CNC machine in the lab, able to cut almost anything from paper to thin wood, after being fed with 2D graphics from a PC. Initially, I thought it was strange that 20-year-old machines were put in the lab, since it aspired to be on the cutting edge of digital culture. Then I realised, however, that this made perfect sense: in principle, a printer for paper and a 3D printer are the same. It is about having the machine realise forms in a material that were created on your personal computer – or downloaded. A FabLab is equally – if not mainly – about the process of 'digital fabrication' as it is about the machines and products of this process. And this process is in a confined form already realised with a desktop printer for paper.

Making use of the different processes of digital fabrication, however, is not as easy as printing a text. Even now this still involves working with advanced software programs to digitally design objects and to operate the machines. Furthermore, with the exception of some low-cost 3D printers that some FabLabs use, none of these are consumer technologies affording easy usage. Often open-source designs with a self-built and prototypical feel to them or industrial-grade machines, these tools do not provide a 'one-click wonderland' of producing anything you design on your computer. Rather, there are complex interrelations of the digital and material side of these processes. Adjusting machines and software and in general improving the process, involving the selection of materials, e.g. for a laser cutter, are needed for this as well. The technical core of FabLabs, therefore, affords a set of skills in digital technologies and electric machines. Making use of the capabilities of these technologies requires an intense process of learning. And for many members of FabLab Karlsruhe and other FabLabs, this process of getting into these technologies, learning about and unfolding them, is an important part of their fascination for FabLabs. As enthusiasts, hobbyists, developers and users of these technologies, what one could call the technological core group of FabLabs have built substantial technical knowledge and skills. And these set them apart from others who want to make use of FabLabs and learn about the machines.

Such individual skills are highly valued with admiration and respect often being expressed for particularly difficult to realise technical objects. The culture of hacking entails meritocratic evaluations to a great extent (Coleman, 2012). But the ethos of openness fosters experiments transcending such individualised approaches to evaluating knowledge. To foster learning and the sharing of knowledge and empowerment many FabLabs offer courses to learn particular technical processes. In Karlsruhe, courses in building or using 3D printers have been offered as well as courses especially for school children. MIT has been running a programme called the 'Fab academy' held in technically advanced FabLabs to train and educate FabLabbers further about digital fabrication and more sophisticated and advanced technologies in this field. Besides such organised learning events, absolutely central to FabLab practices is individual help and support. The ethos of openness is translated by many FabLab users into being open to questions and difficulties by others to which they respond – if their projects leave them the time. Such education and sharing of knowledge, however, as spontaneous as it might sometimes be, is also an organisational skill that needs to be learned in the labs[15]. How to make sure people have the required knowledge about safely running the machines is an equally important question here, as is how to get details about technologies across without overly using expert language, which many are often used to. Social skills are as necessary as technical skills for this. And although there are hierarchies of expertise in FabLabs, the imperative of inclusion fosters experimentation with sharing such expertise. Thus, part of the technical learning in FabLabs is a process about learning social and organisational competences.

Another object has had an important influence on the possibilities of using FabLab Karlsruhe: the room. Already in the planning phase the imagined room was part of the contestations of the setup of the FabLab. When after discussions the group decided to start in a small room to save money at the beginning, the room was turned into a political issue. Although the manifesto read that in principle every technical activity should be possible in the FabLab, the room was used to restrict the variety of technologies. Some in the group strongly opposed the enabling of wood construction in the lab. The sawdust would make the 3D printers dirty and, therefore, be a threat to the most important technology in the lab, they argued. And they added that wood construction would then need a second room, separate from the electronics and printers. Others argued against this and imagined that this is an organisational issue and that with special effort one could enable wood construction and printing in a small room. Such arguments without a clear position by the group as a whole were also mentioned when newcomers were introduced to the planning group and said that they wanted to work with wood in the future. Thus, although sawdust clearly is a technical problem to some electronic machines, this episode illustrates how particular valuations of machines translate into the valuation of different technical practices, which in turn, in a FabLab, are also practices of particular people that are in consequence excluded.

15 A quantitative study amongst different forms of open workshops, including FabLabs, found that these organisations typically highly value learning, education, and the exploration of new forms of working together. In most the production of knowledge is seen as more important than the production of artefacts (Lange et al., 2016).

The room however was not only an object of such technical considerations but also of symbolic design decisions. When a planning group set up an initial layout for the room, considerations were not only about which space would be best to use different tools. But it was also considered which space in the room presented particular tools best, i.e. 3D printers, since at the beginning these were the only digital fabrication machines of the lab. After a couple of months, when the lab was running and the room had filled up with more machines, tools, materials and individual projects, an important task was to restructure the room's layout. Based on experiences with visitors, for some it was important that the 3D printers remain next to the windows so that they could be watched by passers-by. Such symbolical evaluations can be found in other small details of the room. When the lab opened the room was still somewhat sterile. An existing DIY group of 'guerrilla knitters' in a move of sympathy for the lab met one evening, held a course in knitting and left its results attached to the lab's ceiling. Over the months visitors were often shown the knitted objects to exemplify that the FabLab is not only about digital machines. Yet to a regular visitor to the lab it became evident that there was not much change on the knitting side. Rather, the individual technical projects that were either worked on or placed in the shelves to continue work on them later mostly spoke a language of digital fabrication and electronics. Thus, on the symbolic side of the by now far too small room, the FabLab appears to visitors as a space for practices and people interested in digital machines, despite the more inclusive language of the manifesto. However, morally similar to the use of the wiki, whilst no one would stop you from offering courses in knitting or building furniture in the lab, its technosocial setup, which grew out of the lab's history, does not particularly encourage you to do this either. The inclusion of different practices besides the commonly highly valued digital fabrication practices is placed in the domain of individual responsibility.

The start of the building process of the Lasersaur is an episode in which the above-analysed relations of subjects and objects are particularly condensed. The chapter on the Lasersaur analysed this building process in terms of the management of objects, so here I give an example of how people are arranged in the lab in relation to technical objects. Since the machine was financed through a scientific competition about digital society that a colleague and I won, the plan was to use the building process as a demonstration and learning platform for novel ways of engaging with digital knowledge. Therefore, the building process was announced publicly and members of the FabLab were invited to join. This Friday evening eight people, including myself, worked in various constellations on the machine. Even a teenage boy, who was in the lab for the second time, was invited to join. Several laptops were online to read the open-source building instructions and two people with by then the most expertise about the project coordinated the process. An ad-hoc division of labour was created based on the competences and interests of the people. I did not have experience with such industrial-grade materials and technical drawings and some other people didn't either. A hectic process of tinkering with and learning from each other started even though for the frame of the machine highly precise results were required. Holes were drilled in aluminium and many were wrong. Some parts disappeared or could not be found. People stood in each other's way or were desperately browsing the Internet for a problem that was encountered during a building step. Around midnight, however, the frame of the machine sat on the table with some signs of the chaotic building process, and excited, tired and a little proud the group admired it.

Two technically highly skilled members who prepared the project – using a wiki – agreed when one of them said: 'It might have been a little stressful and some things went wrong, but, by and large, we fulfilled the mission of the FabLab.' This mission being to bring a diverse set of people into voluntary contact with technical becoming. From then on, however, the building group consolidated a stronger division of labour. However, at times, other people helped spontaneously with particular tasks. The ethos of openness that was enacted centred around a highly desired machine whose building process was visible to the members of the lab and even open to volunteers to join. Furthermore, the limited space in the room of the FabLab engendered some collaborations because people were necessarily co-present. And interestingly, a couple of weeks later, after much further work to finish the Lasersaur, wood construction massively entered the lab. But now, with the Lasersaur running it was not sawn but laser cut and therefore practically and symbolically a product of digital fabrication.

In this section, I analysed how experimentation with and through the ethos of openness is a central aspect in FabLabs. Such experimentation is fundamentally about manipulating and learning social processes of organising technologies and technical knowledge, which is also about organising people. Openness in the perspective of my analysis is not simply enabled by digital technologies. Rather, experiments with openness are being realised in the constitution and manipulation of a machinic assemblage and heterogeneous interventions into this process. As I have shown, this involves efforts to discursively and aesthetically appeal to a diverse audience and to symbolically enact the ideal of inclusion into FabLabs. This entails competences of design and presentation that some FabLabs and some people in them can mobilise. In Karlsruhe, planning and designing the lab included envisioning a diverse group of users. While there is diversity in the group, still a significant proportion of the group's demographic is close to a mainly male technology and tinkering culture. There are, however, efforts to symbolically and practically transcend this culture to create a more diverse – in terms of people and practices – organisation, although the tensions between discourse and actual practice are clearly visible also for practitioners. It is very significant for such experimentation when new people join the lab with different skills and expectations since they have been challenging particular routines. In sum, one could say that thanks to ideals of openness and inclusion, the group in Karlsruhe as experimental subject has been experimenting with its own possible transformations, which in turn are effects and causes for experimentation. This experimentation, however, is inspired by and strongly rooted in correspondences of people and digitised technologies which form the core of FabLabs. The skills and forms of subjectivity that are entwined with the unfolding of these objects are an important practical medium for inclusion and exclusion in FabLabs. Inequalities in technical knowledge are explicitly addressed through teaching and courses. But to be fully part of the FabLab, one has to learn to correspond with digital fabrication and the people who are already doing so.

In the next section of this chapter I focus on the relations that the FabLab and its members form with others and other organisations. This shows how the FabLab does not simply experiment with itself but also with others and helps trace processes of desiring and exploring particular futures in the practices of FabLabs.

4.3.4 Desiring with a FabLab

In this section I extend the analysis of visioneering practices of creating and shaping desire as part of real-life experiments by focusing on FabLab Karlsruhe and its relations to other FabLabs or organisations. What are the fine details of desiring that takes place in localised imitations, site-specific collaborations and projects that FabLabs and their members participate in? First, the analysis focuses on FabLab Karlsruhe as a medium of desiring and, second, it is analysed how relations to other organisations transform desires.

Imagining with FabLabs

The following picture shows the interior of FabLab Karlsruhe about half a year after the lab had opened its doors. It was also selected as a picture for the website of the lab and with the different people expresses the ideals of inclusion and cooperation. It is, therefore, also a manifestation of desires. To start the analysis I want to point the reader to the objects on top of the table in the lower right corner of the picture. Most of these objects were made using the machines in the lab. In particular, most of them are 3D-printed objects made of relatively cheap plastic, yet these often have irregular shapes such as a vase in a flame-like shape. There were also many more wooden objects, put together from pieces cut by the laser cutter. Actually, based on visits to other FabLabs, I find it highly likely that such objects can be found in every FabLab in the world. Although they seem as if they are decoration, they mainly serve another function in the labs, which is to make the technical capabilities and potentials tangible. They serve as tools for visioneering, for desiring the technosocial possibilities of FabLabs and for making these seem desirable and feasible.

Figure 4.4: Inside FabLab Karlsruhe in late 2014. Photograph by FabLab Karlsruhe

The objects on the table close to the entrance of the lab are particularly important when visitors are introduced to the FabLab and the practices within it, itself an important practice that happens quite regularly. A FabLab member who would give a small 'tour' through the lab would take one or more of these objects and give them to the visitor to more closely inspect these objects and to touch them. The guide would also talk about digital fabrication, about self-built machines and about the member-based organisation of the lab. And as an accessible material trace of this arrangement the object in the hands of the guest would be 'objective' proof of what is done in FabLabs and what can be done in them. The guide would explain that especially 3D printing enables forms to be realised that other manufacturing processes cannot produce and that these things were made in the FabLab. Touching the objects would convey a sense of quality of the objects, which depending on the perspective could either be seen as 'low' or 'high' quality. Furthermore, giving these objects to people also conveys a key message: 'In a FabLab you don't need to be an onlooker, but you are invited to get your hands dirty.' The object-subject-organisation relations that are enacted in this situation of introducing others to FabLabs are about the present of FabLabs, i.e. what can be done there, and about possible futures, i.e. what could be done there if the social and technical capabilities further expand. This also addresses the visitor as a possible future agent in such an expansion: 'You could become part of the lab and be technically empowered to produce novel things.' Therefore, in addition to possibly unfolding objects one must also think of unfinished and unfolding organisations and unfolding subjects that are part of the interplay of desires and lacks that co-constitute engagement in FabLabs (on desiring unfolding objects: Knorr-Cetina, 1997). How does this take place?

Besides the showcased objects there are other objects that play an even more important part in propelling FabLabs forward: the projects of individual users of the lab[16]. Of course, most FabLab practices are object-centred, and making and tinkering with objects are key to most FabLabbers. Yet making these things in the

[16] The importance of such 'projects' for makers and hackers is highlighted in other literature as well (maxigas, 2015; Toombs et al., 2014).

lab is not only about realising one's projects with the lab as a 'tool'. Rather, the shared and visible character of these projects also turns these objects and the lab into a medium for the exploration of possibilities. Such technical projects express the technical capabilities of the lab but also the dimensions of the technical skills that the lab's members have and are unfolding. Therefore, these objects are also important for defining what the FabLab is and what it could become.

Already in the planning stage, projects that members had built and planned to improve in the lab were brought along to the meeting room to present them to others. These included 3D printers, of course, and also self-built drones and furniture. They were materialised images of what was a trend in the publics of the maker movement at that time. In late 2015, when the lab in Karlsruhe had widened its infrastructure, the objects that were made included many 3D-printed objects, 3D printers, toy robots, an electric bass guitar with everything except the screws hand-built in the FabLab, imprints on T-shirts, lampshades made of wood or plastic and more. While the lab was certainly important in enabling the materialisation of the objects, much of the knowledge and inspiration for these objects was acquired from online sources. The public presentation of the projects in labs or online is creating a networked process of desiring, designing and producing objects in a FabLab approach. The most proficient 3D-printer builder in the lab told me that he encountered an open-source project for a knitting machine able to produce clothes. And this made him imagine that a completely different paradigm of producing things for everyday life might be possible – after he had already printed many things. The different technical capability showed that needful things, besides simply 3D printing for a hobby, could be possible in a FabLab and through open digital fabrication.

One of the most 'visionary' projects that emerged early on in FabLab Karlsruhe was conceived by a self-employed consultant specialised in 'open innovation'. He joined the FabLab in its early phase and an idea and question of him became rejuvenated and creatively entwined with the lab. He once lived in a country in the global south and did not like the cheap concrete and metal huts the government was building to provide affordable housing. Why not make a house completely different, mixing traditional crafts and local materials with high-tech and contemporary expertise, he had been asking himself since then. With the FabLab unfolding, he told me, the idea came to life again. He therefore started to work on a project with the aim to create an open-source house for €5,000 made of clay with the help of 3D printing and a networked organisational model. The house should at the same time be customisable, practical, beautiful, ecologically friendly and provided by a company with a business plan similar to open-source software companies, selling service instead of products. Other such plans to 3D-print houses existed in other projects at the time but the organisational model envisioned here was special – therefore this can also be read as a transformative imitation. He tried to build a network of partners with this vision, including the FabLab, a department of architecture at a university and companies. This did not succeed and the project came to a halt. But that it was started is a strong sign of how FabLab Karlsruhe provided the ground to transform imaginations. The FabLab provided the proper milieu to actually be imagined in concrete terms and to be conceived as feasible. The FabLab can be seen as expressing an evident potential of and for novel technologies and knowledge about them (3D printing), ways of organising them (networked, open) and including ethical considerations (affordable, ecological, individual). And this is not confined to Karlsruhe; other FabLabs engendered such projects as well. For example, a project for low-cost open-source prostheses partly made of bamboo was launched in FabLab Amsterdam with unconventional ways of organising the project (see Dickel et al., 2014). Besides simply making things FabLabs are turned into spaces where potentials of unfolding objects are collectively explored. The labs are places for practical and socialised explorations of the objects' possibilities and potentials. Engagement with the futures of FabLabs and their objects is, thus, strongly linked to technical practices in close exchange with objects.

Besides such object-related practices there are sometimes huge aspirations for networking to harness the technosocial potential of a synergy of the labs. Networking is even inscribed in the material and imaginary design of FabLabs, which asks for a similar inventory in each lab, such that the reproduction of things is facilitated. Such networking, however, is far from taking place everywhere equally. Although many share the impression that the network emerged by chance, particularly Gershenfeld and MIT have become key players in creating organisations within the FabLab assemblage that foster and channel networking amongst labs and individuals. For this network, several activities initiated at MIT became important: yearly 'Fab' conferences[17], 'Fab academies' for teaching courses in digital fabrication and the 'Fab Foundation,' to foster networking amongst the labs and also with businesses. In addition to this, Internet platforms have been connecting or at least informing about FabLabs. Above I mentioned the FabLab wiki run by FabLab Ísland for the FabLab network. Noteworthy is a more recent effort through the social media inspired site www.fablabs.io, a site operated by Fab Foundation where individual FabLabs create profiles. Although MIT puts forward the vision and different practices of global networking amongst FabLabs, this is not as straightforward as it is presented. Participation in the conferences and programmes requires resources such as money and time. And the mostly English information on the websites might be helpful, but for now it does not allow for rich digitised interactions and networking.

Therefore, regional efforts for networking are also important besides this centralised network regime that MIT is trying to uphold. There are different examples of how FabLabs in areas or nations set up mailing lists and hold their own conferences, events or meetings. The Netherlands were first to start a national organisation for FabLabs (Troxler, 2014). By now, in Germany many FabLabs have become part of an association of 'open workshops' (http://www.offene-werkstaetten.org/, accessed March 2016), established in 2011, which, however, includes many different workshops, e.g. for bicycle repair, wood working or textiles. There are also visits to other FabLabs that proved to be hugely important in Karlsruhe to see their solutions to common problems in labs. In Karlsruhe, the safety concept was strongly inspired by a FabLab in Bavaria that some people visited. Furthermore, conferences and trade fairs for makers have been taking place across the globe and in Europe for a couple of years now. These are also events where FabLabbers meet each other and present their projects and labs. Yet, although such networking, which involves co-presence in other FabLabs or with people from these labs, takes place, it is limited due to several constraints. The time needed and the demands of locally running a lab which are seen as more important than networking with others have been mentioned in Karlsruhe.

Networking practices are however insufficiently grasped if one only imagines a network of FabLabs. In Karlsruhe, there is a whole digital sphere of the FabLab of mailing lists, wikis and social media where people interact or inform themselves about the FabLab without being in the actual lab. Much of the organisation of the volunteers engaging in different tasks and projects is done via email. This is extended further concerning all kinds of information online – notably open-source projects – which is almost routinely investigated by many FabLab members when there is a question. These forms of digitally mediated exchanges and connections are heavily dependent on the sociotechnical practices for knowledge-sharing and communication available 'online' and their further evolution. Such different levels of networked and networking practices, therefore, turn engagement in FabLabs into an engagement with the Internet utopian vision of a digital, decentralised and democratised society. As I have shown above, this vision already proved crucial in the creation of FabLabs in the first place (cf. Turner, 2006). FabLabs, be it through exploring them 'online' or 'offline', are places to explore and unfold such networked forms of sociality.

Thinking through the practices within and between FabLabs about how possibilities are mobilised and explored shows that doing and imagining are tightly entwined. Be it through engaging with the machines or with the lab, such engagement is always also an engagement with what is not locally present. The networked character of the practices and the observation and sometimes imitation of other projects and FabLabs is creating a sense of fields of possibilities within which local practices take place. Be it in contact with objects

[17] The recent Fab conferences took place in Barcelona in 2014, in Boston in 2015 and in Shenzen in 2016. Especially the latter, in an industrial centre of China, shows how MIT is reaching out to industrial audiences as well.

or FabLabs, local practices are embedded in a dynamic global machinic assemblage that provides imaginative and knowledge resources for what is done locally. As Ingold emphasises, imagination is part of perceiving and acting in a world of becoming with which one entangles (2012). Imagination that shapes novelty is an important yet difficult to attain result of human effort, necessary in conscious transformations or trials to do so; the possible starts to grow in imagination (Bloch, 1995). That a FabLab helps, maybe even engendering the imagination of technosocial arrangements of a new kind and also contributing to believing in their feasibility, is from this perspective a valuable and important effect of them. Yet, through the thorough and intense contact with the practices and technologies in FabLabs, one also learns about the constraints and the difficulties of creating novelty. Be it through the limited capabilities of cheap machines or the time needed to learn about and operate a FabLab, pushing the limits of the possible is hard work if you are in a FabLab.

On this note it is also interesting that grand claims that are often promoted by ‘elite visioneers,’ in relation to FabLabs, e.g. of a ‘third industrial revolution’ (Rifkin, 2012) or of ‘anybody making anything’ (Gershenfeld, 2012), have to my knowledge hardly ever been mentioned in FabLab Karlsruhe. I even spoke to people who did not know who Neil Gershenfeld is. In a workshop that I held in another German FabLab to discuss possibilities for improving the organisation of FabLabs I asked the participants to sketch out visions they thought FabLabs should achieve. Amongst the about fifteen participants were many that had been actively involved in running the lab. Then we collectively explored ideas to take practical steps to realising this vision. Ideas such as new and alternative economics or the thorough spread of FabLabs throughout cities were mentioned by some, but no one thought this would simply take place. Rather, the discussion about how to get there from the present was full of cautious and reluctant utterances and it was emphasised how difficult it had already been to make the FabLab operate well and thrive.

There might have been different reasons for this, including different personalities, but no matter what the reasons are this is further evidence of how imagination and desires in FabLabs are strongly embedded in local practices. And although alternative futures and desires for them are explored, engagement with futures is modest and practice-based. While the practical settings of FabLabs enable imagining and desiring, they also constrain it. Instead of free-floating imaginations and grand claims about how the future will be I met many people whose imagination was tightly entwined with the possibilities and constraints of the present, which of course is seen as a dynamic present with tendencies fostering FabLabs, but also a present where changing a FabLab requires hard work. But shaping desires does not stop at the borders of FabLabs but also takes place in between FabLabs and other organisations. Through a focus on such relationships I show next how there is a sense of experimenting with others and of trying novel things that might change the lab.

Transcending FabLabs

While FabLabs are often addressed as places where individuals can pursue their individual technical projects, there is a less recognised dimension of how FabLabs are being enrolled into projects that transcend the labs. Neither in activists’ nor in academic discourse on FabLabs is this strongly addressed. Here I analyse how experimentation is taking place between FabLabs and other organisations and how this transforms desires. Although FabLabs have an explicit agenda of making digital fabrication accessible to individuals as I discussed above, they are relatively indeterminate settings concerning what such access should be used for. From this results a relative flexibility concerning the settings and projects in which FabLabs take part. This is a further dimension of how FabLabs and people working in them are experimentally unfolding. This indeterminacy was also a prime reason why the FabLab concept transgressed MIT’s idea to experimentally test the usage of digital fabrication technologies. In the following, I discuss how FabLab Karlsruhe became part of projects that influenced the lab’s goals, framing and practices. Due to being relatively indeterminate – not purely for production, not purely for education, not purely for a particular group of people and so on – the FabLab attracted other organisations and their projects.

An organisation whose support proved central to quickly and affordably setting up a running lab in Karlsruhe was the municipality's department for culture. This organisation has been running an area for small businesses and cultural and artistic work in an old, converted abattoir (http://www.alterschlachthof-karlsruhe.de/, accessed 14.03.2016). Drawing explicitly on discourse of the 'creative city' (e.g. Florida, 2003) this was created to foster commercial and non-commercial forms of creativity and innovation. The tenants are selected by the municipality to create a mix of knowledge and cultural work which together with the conversion of the abandoned industrial site signifies a move towards 'post-industrial' innovation within the city. Furthermore, with subsidies for non-profit organisations and artists the area also challenges the neoliberal city model which favours free markets, corporations and consumption (Graham and Marvin, 2001). When the FabLab applied for a room, it was seen as a space that would also benefit the artists on site and self-employed people. The FabLab now does not only contribute to the area's allure of 'creativity' but also benefits from its diverse users and flows of visitors. There is a general sense in the FabLab that it fits well to the old abattoir and its agenda. Karlsruhe is not the only place where FabLabs were enrolled in projects of the municipality. Barcelona in summer 2014 announced that they were to become the world's first 'Fab City' during the annual FabLab conference, with a FabLab being planned in each district (www.fab10.org/en/symposium, accessed 08.04.2015; Smith, 2015). In such cooperations one can trace strong differences to the utopian communes of the US counterculture, so influential for the cultural imaginary of digital technologies which settled in the country, in exile, 'outside' society (Turner, 2006). Now FabLabs are resonating with certain tendencies 'within' society and cities.

I have already discussed how the transdisciplinary project Quartier Zukunft was important in the early phase of the FabLab and this was also due to the project's initiative to host a 'repair café' in Karlsruhe. When FabLab Karlsruhe was still in the planning stage, with much discussion and little tinkering, many in the FabLab group welcomed the first 'repair café' as an event to get ones hands onto technology. Quartier Zukunft organised the event together with citizens, the FabLab and other local groups, and the aim was to help people repair broken stuff during this particular event. The contemporary form of repair café was initiated in the Netherlands in 2009. This is a small organisation is spreading knowledge of this concept worldwide, with hundreds of local initiatives holding their repair cafés. Similar to FabLabs, this organisation makes use of the Internet, a loose basic model of what a repair café should be and voluntary structures. Repair cafés imagine themselves as events for changing consumers' perceptions and usages of their technologies and, therefore, as critically engaging with the issues of waste and obsolescence inherent in the industrial system (http://repaircafe.org/about-repair-cafe/, accessed April 2015)[18].

The FabLab was part of organising the café and was to conduct the electronics repairs due to the skills of the participants from the FabLab. The actual event was seen as the first 'materialisation' of genuine FabLab practice: tinkering with stuff and showing the possibilities of 3D printing. Even before the repair café was planned, there had been an email discussion in the FabLab group about 'planned obsolescence' and FabLabs as places for repair and anti-consumerism. During the repair café many things were repaired by the FabLabbers, although the 3D printer that was brought along only served to show its capabilities. The 3D printer, however, embodied a usage scenario of a FabLab, possibly printing all kinds of parts for repair by simply producing them. In the repair café, often small technical solutions did the task, but mainly it was about a social intercourse amongst people that transgressed service centres and professional repair (often more expensive than buying new things), mediated by broken objects and an ethics of joining forces in the flows of their transformation. At the time of writing, the repair cafés still continue every couple of months and find resonance amongst FabLabbers and people who want to repair their stuff.

[18] The issues of waste and obsolescence are already addressed in Illich (1973) and Urry (2014, chap. 7) shows how tremendous amounts of waste are offshored and moved out of sight of consumers to create problems elsewhere.

I want to point out an event which involved myself as action researcher. In summer and autumn 2014, Julia, a colleague of mine, and I led a project trying to combine technology assessment, the FabLab and citizen participation in investigating changes to knowledge due to digitisation (see www.manifest-digital.de, accessed 20.04.2015). The concept drew on ideas of public engagement in science and technology and on Responsible Innovation. Furthermore, we wanted to try out how a FabLab could be turned into a place where technology assessment and civil society meet. Most of the handful of FabLab members who helped organise the event were particularly attracted to the idea, since they thought the FabLab is not only about making things but also about reflecting on technology in society. With the project we had applied for a science communication challenge, which we later won and which provided €10,000 for the project. Several public workshops, which we co-organised with members of the FabLab, were held to discuss the digitisation of knowledge and to practically experience it in engaging in projects and the machines in the FabLab. We also included some aspects of the building process of the Lasersaur in these workshops. Instead of only making things, these workshops turned the FabLab into a kind of 'science shop', a place for explicit reflection and discussion: different aspects of digital technologies and their entwinement with knowledge were discussed and practically explored in the lab. The public event attracted people who otherwise would not use a FabLab. The project led to different ways of engaging in 'research' and to a different enactment of the FabLab, a co-becoming. Certainly, for us, this was an experiment in trying out different practices of research and the FabLab afforded itself as a public laboratory (Schneider and Hahn, 2015).

This selection of different ways in which the FabLab became part of projects from 'outside' the lab could be further extended. For now, however, these examples show how FabLab projects are insufficiently understood if one locates them only within the history of FabLabs[19]. There are other sources of ideas and practices that can be made to correspond with FabLabs and people interested in them. Through this other projects participate in co-defining what FabLabs actually are and might become. The FabLab discourse on inclusion on a trans-individual level also enables the inclusion of different projects and goals for which FabLabs can become experimental settings. Part of this is that many FabLabs, such as the one in Karlsruhe, are relatively indeterminate in their goals and offer multiple points of interest and entry for other projects.

In the three sections above I have analysed how experimentation is based on a diverse collective machine of imaginations and practices that is shaped by and shapes desires. Observing others through different channels such as the Internet or co-presence and in turn imitating practices and projects is central. This can take place when reproducing or transforming technical projects, when imitating practices from other FabLabs or when FabLabs take part in projects of other organisations. In addition and complementary to an individualised approach to using and framing FabLabs as places where individuals work on technical projects, this dimension brings the organisational dimension into view. FabLabs that participate in such processes enact themselves as experimental places that try out different projects and agendas, where an intended diversity of the users is also linked to a diversity of goals that are pursued by or with a FabLab.

Even though there is so far no clearly defined social space for FabLabs – do they belong to the commercial realm, to educational institutions etc.? – FabLabs can unfold differently in the interstices of established institutions and be enrolled into wider projects. Therefore, the ways in which FabLabs are being legitimated and made desirable, besides access to digital fabrication, differ widely depending on the local circumstances and histories of different labs and they depend on the machinic assemblages in which FabLabs take part. In addition to the 'creative individuals' who are addressed in the mainstream FabLab discourse one needs to take these forms of practical and imaginative networking into account with which these individuals – and their organisations – are entwined. In providing a flexible space for different projects and imaginations such FabLab practices do not only contribute to mobilising and pushing the limits of the possible in the overall

[19] Many different organisations from universities, design centres, companies, cultural hubs and so on have been running or cooperating with FabLabs (Lhoste and Barbier, 2015; Kohtala and Bosqué, 2014; Troxler, 2014; Walter-Herrmann and Büching, 2013).

FabLab assemblage. Rather, FabLabs themselves enable practices of transforming desires in the first place, when besides access to tools there is access to imaginative resources and social dynamics that foster the creation of technical or organisational projects. In FabLabs different technosocial futures of digital technologies can be practically explored in experiments that treat objects, subjects and organisations as unfolding prototypes of a time to come. For such experiments to take place, however, a certain stability of the present is necessary as well, as analysed in the next section.

4.3.5 Maintenance and repair

There is an often overlooked aspect of modern technology: its wear and tear and its breakdown which is being taken care of in practices of repair and maintenance (Graham and Thrift, 2007). 'Repair is a neglected, poorly understood, but all-important aspect of technical craftsmanship,' writes Richard Sennett (2008, p. 199). And indeed all the experimentation that I wrote about is strongly concerned with creating novelty and with producing technosocialities. However, experimentation is uncertain and surprising, and things do not always turn out as planned. Therefore, maintenance and repair is crucial for experimentation to take place and fixing broken 'things' is part of FabLab real-life experiments. However, such maintenance and 'repair' does not only take place with objects but with subjects and organisations as well.

To really understand the digital fabrication machines that FabLab Karlsruhe as well as many other grassroots FabLabs utilise you have to look in the rubbish bin of the lab. No matter which day, you will find many broken items and failed objects that were damaged during producing them or were wrongly designed. Such trial and error is central to the process of digital fabrication where you can get quick – and mostly affordable – feedback between the digital design of objects and the material realisation of them. Throwing failed objects away does not hurt that much and encourages users to try things out. However, in FabLab Karlsruhe sometimes many users want to try out machines and operate them differently and sometimes without the necessary care. Therefore, the hours during which people were building, repairing or adjusting the machines in the lab add up to a tremendous amount of time. The Lasersaur, for example, after it was accidentally broken, was out of order for about six months. During this time a small group decided to improve the machine's design, which then became such a complex process that it was difficult for others to join and help, and additionally volunteers for this task were scarce. In reaction to such breakdown of machines from the beginning onwards, a tighter set of rules was developed in Karlsruhe. While in the lab's early days the usage of the machines and the lab in general was formally little regulated, particular restrictions were introduced over time. In particular the increase in machines that were considered risky, such as the Lasersaur, gave way to considerations about how to make sure that the machines are used correctly. Many explicit procedures came into being, such as doing introductory courses before one can use the machines, and the usage was more clearly documented. This is a learning effect of the experiment of making machines accessible to any member of the lab.

And maintenance is not only about machines for which materials need to be bought and tested but also for the room, which needs to be cleaned and kept orderly. Mostly, such tasks of maintenance and repair are being taken care of by particularly active members who already spend much time in the lab. This is not confined to Karlsruhe; other research also reports on the demands and time needed to run FabLabs on a day-to-day basis, which takes many organisational resources away from other things – experimentation, for example (Kohtala, 2016; Hielscher et al., 2015a). There have thus equally been efforts to oversee the inflow and outflow of materials as well as people and to create rules for the usage of the lab. While in the early times visits and even usage of machines by non-members happened quite regularly, it has become a strategy to move such use of the lab to the regular 'open days' once a month. Such events where 'everyone' can use the FabLab are written as a requirement in the Fab Charter, published by MIT. During these events, non-members are explicitly invited to get to know the FabLab and to freely use the machines. Non-members are typically not rejected when they visit the lab at other times, but the open days, which are prominently featured on the website, entail that volunteers are explicitly there to talk to and to help people. In particular regular users had felt that often time to work on their projects was taken away when newcomers appeared without notification. The open days are thus intended to protect material and social resources from unplanned usage. This could be seen as a decrease in openness but it is also a learning effect about how to maintain a common resource open to particular people who help to sustain it.

Furthermore, many collaborations in FabLabs take much effort to be maintained. A collaborative demand beyond individual labs is the maintenance of online documentation. For many projects online documentation is often planned and partly realised, so that others can draw on the digital information. However, well-documented projects take a lot of time and goodwill. While a local solution to a particular problem might have been found, documenting it means a fair amount of additional work. Inside FabLab Karlsruhe, as with other FabLabs that largely run on voluntary work, it is a huge question as to how to uphold a friendly and collaborative atmosphere and still get things done. From the beginning, the internal governance of the organisation has been the central task in setting the lab up. Concerning collaboration, however, you cannot simply regulate everything with rules. Friendliness, empathy, responsibility and other virtues of intercourse are important here, such that the volunteers want to collaborate with each other and with the FabLab. However, at times such social bonds for collaboration broke down, e.g. when people with different opinions clashed or others stopped taking part in activities for which they held central roles. Such situations when collaborations broke down or were not going well have been part of the FabLab and probably will remain so. However, repairing and maintaining a collaborative atmosphere might be an organisational skill that can be learned in these interpersonal small-scale experiments.

There is a particular tension in the ‘maker’ subjectivity between maintenance and experimentation. Makers and the maker movement have been addressed as the revolutionary figures of our time in public discourse. Equipped with the latest digital tools and an anarchic drive to tinker and to hack, makers were supposed to usher in the ‘third industrial revolution’ or to even abandon capitalism altogether. And if such big transformations are not addressed then makers should at least reinvent work, technical objects and collaboration in a digital age (Dickel and Schrape, 2015; Rifkin, 2014; Troxler and maxigas, 2014; Walter-Herrmann and Büching, 2013; Anderson, 2012; Gershenfeld, 2012; Gorz, 2010b). Yet, far from being a new revolutionary, many practices and subjectivities that are being subsumed nowadays under the umbrella ‘maker’ have a long and often conservative history. Many DIY fields have been tightly entwined with mainstream ideas about home ownership and gender relations, with men tinkering with wood and women knitting, for example (Atkinson, 2006). And although open source and digitized, many maker projects draw on resources and histories in such fields of hobby and enthusiasm for particular technologies without much enthusiasm for social transformation. Above I have already discussed how many maker practices, projects and subjects are mostly male- and technology-focused cultures.

Furthermore, even in ‘maker’ discourse the idea of the individual realising their projects with the help of novel machines is dominant. In its utopian shades this discourse promotes a rather homogeneous society where everyone does these practices and where in turn everyone is the same. This does not take differences and divisions of labour, central for complex societies, into account; rather, it maintains an ideal that is already known to some in maker ‘communities’ and does not seek experimentation with differences. And this is also the way in which FabLabs are typically used: individuals pursuing their individual projects. When during a workshop I held in another German FabLab the question was raised why the lab would not more strongly engage in larger projects and try to reach other organisations, a central organiser of the lab answered: ‘Well I think makers do not always want to do additional things. It is already hard enough to make time for your own projects and then you want to work on them.’ In addition to individualised tinkering, business has been catching up with the maker movement and allows many makers to pursue their activities as individualised consumers of parts and objects especially made for maker projects. Seen from these angles, ‘the maker’ can also be seen as a rather conservative figure seeking individual joy in the evenings after a nine to five job, far from a ‘revolutionary’ (see also Troxler and maxigas, 2014). Thus, in contrast and in partial tension to a revolutionary discourse of making, many traditions and structures are being maintained in maker practices. One might even speculate that the existence of such practices enabled the relatively quick formation of the maker ‘movement’ as an integration of different elements and traditions. Then, the positive framing of ‘making’ could be considered a symbolic repair of DIY practices that faced the threat of becoming irrelevant in an accelerating consumer society.

In Karlsruhe, the majority of the lab’s members follow an individualised tinkerer approach, turn up irregularly and only marginally contribute to the organisation and transformation of the lab. There are, however, a minority who puts much effort into running the lab and exploring possibilities to widen cooperations with other organisations and other labs, for example. They would also identify themselves as makers, but they are part of the particularly active minorities in such member-based organisations that can be found in other areas of civil society as well (Zimmer, 2013; Zimmer et al., 2004). And indeed, involving members more widely in the tasks of running and extending the lab is in Karlsruhe seen as a prime goal after almost two years of an open lab. There is, thus, within the ‘maker movement’ a tension between maintaining the routines of individualised DIY practices and engaging in the experiments, networked projects and collaborations that the collective machine of FabLabs is affording as well. And although many ‘makers’ might not do that many socially creative things, in Karlsruhe they help to sustain the lab, if only through member fees, and, therefore, help to enable experimentation as well. Experimentation in FabLabs needs resources. In the following I therefore turn to the experimental economies that FabLabs have been participating in.

4.3.6 Experimental economy

‘And who pays for that?’ I was often asked that question when the discussion was about FabLabs. It is not that surprising. Most modern technologies, their invention, production and usage are about money and particularly profit; we have become used to a close intertwining of capitalism and technology[20]. This has become so taken for granted that Ulrich Beck (1997, pp. 115–120) only dares a ‘thought experiment’ to reflect upon what if technology was autonomous from economic dictate, what if it was not simply a means for profit? Would society then be freer to choose its technologies? Not only for intellectuals, but also in everyday life, not thinking about technology and its advancement in the sense of a capitalist ‘industrial technology’, including the way in which the unfolding of technology is being organised, is hard to do[21]. Besides the industrial paradigm that went global in the 20th century, neoliberalism has boosted the understanding of technology as a purely capitalist affair during the past decades: intellectual property regimes were tightened, research and education have been commercialised, offshoring stabilised mass production, technological development has been concentrated in large companies, and all this is justified through ‘the market’ as the ‘best’ way for social organisation (Sayer, 2015a; Urry, 2014; Tyfield, 2013; Harvey, 2012; Mirowski, 2011; Crouch, 2011). Strangely, however, STS have largely ignored the question of how political economy is entwined with technoscience and knowledge production. Although this is so tremendously obvious and important, it is an only recently emerging research agenda (e.g., Birch, 2013; Tyfield, 2012; Lave et al., 2010). This section is an effort to advance this agenda through an analysis of the experiments with economies in FabLabs.

[20] Marx (1976) made the classic argument for this relationship: each commodity has ‘exchange value’ and ‘use value’, the latter pointing to the technical character of commodities. From this, however, does not follow that everything with use value necessarily has exchange value. Yet many capitalist practices are keen to commodify the things which are not yet endowed with exchange value and circulated in markets. Noble goes further and argues that ‘modern technology’ is capitalist technology (1977). While certainly most of the modern technologies are capitalist, there are also modern state-funded technologies and technologies developed in commons economies such as some open-source software.

[21] Although some theorists tried to do that their analyses remained largely in a speculative mode (e.g., Illich, 1973; Mumford, 1964).

Here, I analyse how questions of economy matter a great deal for the experiments of FabLabs and how FabLabs experiment with economic matters. For this, however, we need a notion of 'economy' appropriate to the practices in FabLabs. First, economic practices, in general, and in FabLabs in particular, are insufficiently grasped if one only considers capitalist processes. Besides market exchanges and paid labour, economies involve forms of provisioning, gifts and exchanges which are not tied to flows of capital. Furthermore, there are increasingly settings of commons economies, supported through digital technology, that complexly entwine with capitalist processes (Mason, 2015; Sayer, 2015b; Harvey, 2014; Hardt and Negri, 2009). Second, there is paid labour and various forms of unpaid labour, and humans produce themselves and their societies through both, as Marx argued, although in capitalism paid labour is crucial to most people to provide for their lives. Questions of paid and unpaid labour are therefore bound to questions of human life, time and human becoming, i.e. how much time people have to spend or can spend on different activities (Srnicek and Williams, 2015; Gorz, 2010a; Marx, 1976). Third, questions of the access to and power over resources are within capitalism based on unequal distributions of capital ownership (as money or objects). Such ownership can be organised differently, e.g. as individual or collective. Fourth, the complex arrangements of different economic practices always involve moral arrangements that legitimise particular distributions of wealth, tasks and responsibilities, and a 'moral economy' serves to evaluate economic relations (Sayer, 2015b). In the following I examine ways in which different economic relations, forms of labour and moral justifications are entwined with experimental dynamics in FabLabs.

An important economic practice in FabLabs is often said to be 'commoning,' which 'produces or establishes a social relation with a common whose uses are either exclusive to a social group or partially or fully open to all and sundry' (Harvey, 2012, p. 73)[22]. Practices of commoning have been the reason why many open-source projects have been interpreted as beyond markets or even capitalism (influential: Benkler, 2006). However, such dichotomous conceptions no longer fit the realities. The moral economy in FabLabs is strongly based on positive valuations of commons. The explicit promotion of sharing of knowledge, open usage of the labs and decentralisation of technological development are strongly rooted in conceptions of knowledge commons. But this does not mean that FabLabs are beyond capitalism – there is a growing literature on how commons are being exploited by or are created to serve private interests (Söderberg and Delfanti, 2015; Ritzer et al., 2012). However, this moral economy does not neatly fit into the dominant arrangements of economic practices and justifications for which under neoliberalism private knowledge monopolies have become central. The tension this creates provides space for debating moral economy and searching for economic practices in line with the 'FabLab moral economy' in the making. In the following analysis I challenge either-or thinking and trace how there are entanglements of commons, private property and commodities in FabLab practices. Key to the analysis is a shift from a commons (product) to commoning (process) that produces and maintains a commons and entangles or disentangles it from other economic relations.

First of all, there are different forms of ownership of FabLabs. As I have shown above, there are the FabLabs as initially conceived by MIT for which the Fab Foundation estimates costs for machines and materials of $40,000 to $100,000 – there exist, however, labs with even higher initial budgets (http://www.fabfoundation.org/fab-labs/setting-up-a-fab-lab/, accessed 13.04.2015). Many of these are often hosted by another organisation and have employed staff for running the lab. As international networkers in the FabLab scene report, many such FabLabs were set up with initial funding, e.g. by a university, but many are expected to become financially autonomous after a certain time. Others started right off as commercial FabLabs. For these labs, finding suitable business models is a big issue (Hielscher et al., 2015a, pp. 32–33; see also Troxler, 2010). Other community-owned, grassroots FabLabs, such as in Karlsruhe, face different economic realities. FabLab Amersfoort started with €5,000. In Karlsruhe we started with no money and within

[22] Harvey's definition captures the fact that many commons are not for 'everyone' but are based on particular relations amongst particular people as members of specific commons.

the first year the equipment that had accumulated in the lab, mainly through donations by individuals or companies (mostly from the IT and 3D printing sector), to my estimations had a monetary value of about €15,000. The bills for rent and other things are paid by the members, who each pay a monthly fee they decide themselves from €1 onwards with a suggested amount of €20 a month. Karlsruhe, like many other grassroots FabLabs, is community-owned and also governed by the members, who through their individual monetary contributions sustain their commons of the workshop.

Second, FabLabs and FabLab practices often draw on wider knowledge commons, e.g. in open-source projects. The comparatively low cost of setting up the lab in Karlsruhe owes much to the key machinery – 3D printers and laser cutters – being built based on open-source designs. With only the materials being bought and unpaid labour used to build the machines, the cost of this infrastructure, although still several thousand euros, was much cheaper than acquiring standard commercial machines as mainly advocated by MIT. Such relatively cheap access to tools, materials and knowledge is also key for many tinkering projects in the FabLab, which often draw heavily on networked and public knowledge and objects. However, one must also add that many of the materials used for the projects, such as electronics components, are bought ‘online’ in globalised supply chains, which also enable individuals to acquire components at sometimes spectacularly low prices. Waiting for the delivery from China or elsewhere is a part of many maker projects that I encountered in Karlsruhe. Yet the combination of accessible knowledge, individual expertise and relatively cheap industrial materials have lowered the cost of obtaining ‘FabLab stuff’ during the past years. This is a central politico-economic aspect that has facilitated experimentation with these technologies and the spread of the knowledge commons since the financial effort for experimentation has come down.

The relatively cheap machinery that can be found in many FabLabs, however, is not only an economic factor in terms of its cost but also in terms of its capabilities. As Marx would have it, means of production are an intrinsic part of economic arrangements. These technologies co-define what can be produced in a FabLab and how. 3D printing is mostly mentioned concerning the capabilities of FabLabs. This technology has seen significant changes during the last ten years and created fascinating products. Yet, as discussed above, as of now there are many limitations to the materials, quality and the forms that can be produced with these machines in FabLabs. Other CNC machinery that is typically used is comparable to entry-level industrial-grade machines, which also have limited options concerning materials, sizes and precision. A central aspect of the changes of the economic arrangements in and with FabLabs are, therefore, also the unfolding technical capabilities of these machines or the absence of such further unfolding in techno-economic spheres that are accessible to many if not most FabLabs. Yet technical capabilities are not merely to be found in machines but also in the capabilities of people and their imagination. Part of the means of production are also the knowledge commons enabled through the Internet, which turn individual labs into links in vast networks of technical knowledge.

Third, there is the question of contributions to knowledge commons, which are central besides the machines to FabLabs and their culture. In Karlsruhe, visitors often try to understand what the FabLab is good for, and many have asked whether one can come with an idea or a design, have it produced by members of the FabLab and collect it afterwards. This idea of the FabLab delivering a service is typically negated in the answers. Instead, it is explained to the visitor that one can join the association and learn how to realise the idea or the design by oneself. Similarly, amongst the members, although there is mutual help, each one would be required to do most of the work on their projects themselves. This effectively shows a central aspect of the ethos of openness. People can use the FabLab but they have to learn to become an individual user capable of using the lab, capable of participating in this commons. Besides the knowledge for usage this also means being able to eventually pass this knowledge on to enlarge the commons. Another aspect of this enactment of the ethos is also that the projects being done in the FabLab are visible to others and share in the commons of ideas present in the lab. Besides such emphasis of individual empowerment, however, individual learning also means relief for others from teaching and taking care of others’ projects and in turn having time to go about their own ideas. While such reciprocal relations are central to commoning in individual labs, reciprocity is more difficult to establish in 'online' knowledge commons. There, much explicit knowledge is accessible, yet contributing to this can be very time-consuming and difficult, and it needs the readiness to do so as well. You can find members of the Karlsruhe lab who are open-source enthusiasts and in different ways contribute to online forums and projects, if there is time available and the local tasks permit it. There is even a FabLab Karlsruhe design of a 3D printer that was precisely documented by its designer over several months (http://wiki.fablab-karlsruhe.de/doku.php?id=projekte:hexagon, accessed 21 July 2016; see also the Lasersaur chapter for the demands and difficulties of online documentation and knowledge-sharing). However, many new ideas and successful projects in Karlsruhe are not documented online.

Another way in which commoning inside and beyond a FabLab is governed can be found in FabLab Amsterdam. This was one of Europe's first labs, founded in 2007, and has been influential in popularising the concept in Europe. I met the lab's manager in 2013 and he told me that the biggest challenge has been to make the lab financially sustainable and independent from the funding by its host organisation. Even though the lab is mainly only usable through renting and for special events, an idea by MIT and the initial network of labs, also written in the Fab charter, is still being practised: the open days. Every Saturday the lab opens its doors for any user. But in Amsterdam they are required to pay for the use of the machines and courses for introductions into using them. The fees for using machines are rather high (between €10 to €50 per hour), compared to the member fees in Karlsruhe (€20 suggested per month). There is, however, a possibility to get fifty per cent of the money back if the users document their work on an online platform under an open-source licence (http://fablab.waag.org/open-day, accessed August 2016). The FabLab's host organisation has been a project partner in establishing this platform for knowledge-sharing (https://www.open things.wiki/, accessed August 2016). Although controlling whether work has been correctly documented is additional work, this is an offer by the lab, using market logics, i.e. monetary incentives, to foster 'online' knowledge commons. Here, we have another enactment of the ethos of openness that is largely based on private property relations inside the lab because users rent the machines, yet emphasises commoning beyond the individual lab 'online'.

Furthermore, there are also particular relations between FabLabs and businesses. In FabLab Karlsruhe businesses and commercial activities are accepted and even welcome, but it depends on what kind of practices these are. Within the lab, some people who work in technology companies or are self-employed use the lab to enhance their skills and knowledge about particular technologies, and it is difficult to discern what is hobby and what is professional. Within the first two years two commercial activities started in the lab. The open-source 3D printer design by one of the members of the lab was licensed to a small online electronics shop by another member who now sells assembly kits for the design. For each kit, however, a fee is being paid to the association – and not the designer. Another company was started by a member drawing on his experience with the FabLab. This company contributed some expensive materials to the Lasersaur build, in return for being able to use the machine for prototyping its early products. Reciprocity is being established through strong mutual contacts and a shared engagement in the commons of the lab, but there are also two other examples with industrial firms that show how relationships between a grassroots FabLab and companies can be established.

The above-mentioned 3D printer design received much attention in online communities and was acclaimed for its precision. This led to a contact to an industrial company that produces metal parts for machinery. And since they have realised that their parts can also be used in 3D printer building they made a donation of parts worth a couple of thousand euros to the lab. These parts were used in 3D printer building workshops in the lab and drastically lowered the cost of the assembly. This relationship even led to offers to build exhibition models and hold courses concerning 3D printing in the company. Another industrial engineering company approached the lab in Karlsruhe for help in a project of the company. They had plans to set up a workshop similar to a FabLab in their company to facilitate the participation of non-technical employees in technical prototyping. Even they were welcomed to the lab and advised several times concerning the organisation of a FabLab. On the side of the company this led to dramatic changes in how they conceived their lab and a shift from a machine-focused approach to an organization-focused approach. In return for the consultation by some members of the Karlsruhe lab the company donated some tools that they produced, worth several hundred euros, to the FabLab. And both results were proudly narrated later on in the FabLab. The FabLab members were proud that they could teach this company that many regarded as producing high-quality products and, moreover, the tools were seen as a benefit for the commons of the lab in Karlsruhe. This episode is also interesting in respect to the flexibility and perception of the concept of 'FabLab'. The company planned a FabLab with similar machinery and ideas of inclusion but of course vastly restricted inclusion only within their organisation. Even though these two FabLabs are starkly different, the individuals who participated in this contact could meet on a certain understanding of a FabLab as a place for sharing machines and knowledge. Both of these examples with industrial companies show, however, how different conceptions of reciprocity can be. With the industrial companies using their standard approach of 'hard' facts of money and materials to establish relations, the FabLab used its expertise in special technologies and the social and organisational knowledge to participate in this exchange. There was mutual benefit in each case, but it remains to be seen how in the future similar cooperations play out, and whether they will 'colonise' FabLabs with industrial logics.

Also on MIT level, there are efforts to connect business and FabLabs. Most prominently, the Fab Foundation launched two activities in 2014 – www.fabconnections.org and www.fablabconnect.com – which aim at bringing FabLabs and their users in exchange with companies which might want to cooperate or are looking for innovative people and ideas. These were set up to foster the further development of the FabLab 'network' and the capabilities of FabLabs (see Hielscher et al., 2015a). MIT also positions itself as a gatekeeper for such exchanges, drawing on the usually good relationships between (technical) universities and industry (Lave et al., 2010). Gershenfeld and MIT argue, however, for business activities which benefit FabLabs instead of simply exploiting the 'free' knowledge there[23]. The Fab Charter states: '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' (http://fab.cba.mit.edu/about/charter/, accessed 13.04.2015).

However, there are also companies such as Chevron (one of the world's largest oil corporations) which have issued a grant to MIT to launch ten new FabLabs especially dedicated to education in natural sciences and technology (http://www.fabfoundation.org/2014/09/fab-foundation-launches-fab-lab-for-innovation-and-hands-on-learning-at-ca-state-university-bakersfield/, accessed 15.04.2015). Whatever the reasons for this are, this shows how even large companies, not particularly known for bringing well-being to the world, try to get a piece of the moral economy which is enacted by FabLabs. This led to controversial discussions during Fab10 in Barcelona between critics and pragmatic supporters of this relationship (Hielscher et al., 2015a, p. 27). FabLabs can no longer be seen as a nice little subculture. Others in different contexts of political economy have become aware and raised their stakes in trying to influence the further trajectories of the FabLab machine – which from the beginning has been defined in between the co-functionings that it engendered. Therefore, at MIT and in Karlsruhe we see practical and discursive imitations of trials to link up the organisational forms and moral economies of FabLabs with business in order to create different versions of 'Fab economies'. Such links, however, have been established before in other cultures of 'openness'. Already in free software in the 1980s commercial activities were considered appropriate as long as

[23] In very different variations, such ideas of connecting corporations and 'crowds' in producing knowledge are being debated in discourse on 'open innovation' or in projects such as the UK's Big Innovation Centre http://www.biginnovationcentre.com/, accessed 15.04.2015. See also Chesbrough, 2003.

they participated in sharing the software code. And nowadays ‘open-source software’ has become a common approach in the IT industry – without much left, however, from its emancipatory ideals in the beginning (Schrape, 2016; Kelty, 2013). This does not however necessarily mean that the ‘Fab economies’ will equally be absorbed by established techno-capitalist logics. Changes in political economies do not have simple linear patterns.

Since unpaid forms of labour have played a large role in establishing and sustaining many knowledge commons that FabLabs benefit from and participate in, questions of time available to individuals arise. In respect to the political economies of ‘openness’ and Internet-enabled sharing, ideas of an unconditional basic income have been advanced to free people from the necessity of paid labour (Mason, 2015; Moulier-Boutang, 2011; Gorz, 2010a). Similarly, the average working hours per week and levels of education would also possibly strongly influence ‘Fab economies’. As Tyfield (2013) in his discussion of ‘open science’ (which has a family resemblance to open-source technology) points out, however, a transformation of a particular settlement of political economy is a systemic change, involving a new moral economy, successful economic practices, positions for actors and institutions providing for the reproduction of this system. Such a transformation is, thus, also a process entrenched with power and conflict, and without guarantee of success. A single change such as an unconditional basic income is unlikely to deliver all of this.

However, not everything needs to be ‘settled’ for FabLabs to exist, and this ‘unsettledness’ is a main reason for experimentation. FabLabs do not provide the answers to different crises in the political economy of technology, but provide particular questions for transforming the moral economy of knowledge production and corresponding experiments with novel TechKnowledgies. FabLabs can be seen as experimenting with fundamentally reworking conceptions of technology and knowledge but they have to be seen within a far wider tendency to ‘open (source)’ and ‘digitise’ aspects of knowledge and technology. And FabLabs experiment with evaluations of what constitutes ‘good’ technology, what is (‘good’) innovation and in turn also touching wider questions of well-being and flourishing. The machinic assemblage of FabLabs enables concrete experimentation with these questions in discourse and practice which can, without guarantee, be creative. And this is about much more than money. In FabLabs combinations of different economic relations, forms of labour and moral economies are being experimented with. This creates spaces for evaluations and contestations of these arrangements in between Silicon Valley-esque techno-entrepreneurship, hobby tinkering and ideas of solidary peer-to-peer economies. And in turn it is this plurality which is a sign of and a driver for experimentation, which is as of yet an unfolding process without definite results in politico-economic matters.

4.4 The TechKnowledgy of open digital fabrication and its organizational forms

This chapter asked how the global collective machine of FabLabs has been unfolding and how FabLab Karlsruhe was established within this process. The answer that this chapter provided is that FabLabs have been unfolding as a real-life experiment, based on various interventions to test and learn about digital fabrication in public. The surprises, results and technosocial changes that this collective process created have been entwined with the emergence of the TechKnowledgy of open digital fabrication. For this TechKnowledgy, FabLabs have not only proven to be sites of demonstration and testing but also of exploring, transforming and learning about this way of producing and organising technology and knowledge. After summarising the analysis of collective experimentation, this concluding chapter turns towards the insights into the TechKnowledgy of open digital fabrication.

I have argued that FabLabs are real-life experiments, creative processes of interventions in social reality to learn to solve particular problems. The mode of analysis has traced the contours and dynamics of this experiment along the emergence of a machinic assemblage, which has been an enabler for experimentation and the product of the real-life experiment at the same time. Such a recursive logic is key to real-life experiments. Yet the analysis has also revealed that there is no single centre or even prime agent of this experiment. There are many different sites and individual FabLabs where individual people do different things and experiment locally. The history of the FabLab machine is particularly influenced by the pluralisation of these sites. FabLabs bifurcated from a confined experiment at MIT into a global decentred machine with the emergence of grassroots FabLabs from around 2010 onwards. This bifurcation is not a definitive cut with beginnings and ends, but instead enlarged the experimental fields for FabLabs, which are now forming and transforming the global machinic assemblage. Such highly networked and globalised processes as FabLabs, therefore, need to be approached in thinking unity in diversity and diversity in unity. This is necessary for the differences amongst the labs and for the different practices that a FabLab can attract and afford, something which the chapter has shown concerning FabLab Karlsruhe.

Imitation is a key principle of how FabLabs ‘travel’ across the globe and how streams of desires, objects, people and organisational processes are being entwined to form particular FabLabs. Such imitations are never exact copies but attune FabLabs to local circumstances and create difference and novelty. Practices of imitation are important practices to collectivise and distribute experimental agency. Through providing cohesion, similarity and creativity, practices of imitation are important in creating such a decentred experiment. I have analysed how in particular the forms of visibility and networking enabled by the Internet play a key role in engendering imitations of FabLabs so rapidly across the globe and how these cultures of visibility also create observations and inspirations central to collective experimentation. Entwined with such visibility, technical objects for FabLabs became increasingly available and accessible, and people started to desire FabLabs and tested organisational forms that would enable imitations of them. An important part of imitation is the exploration and circulation of desire for which FabLabs have become places to spread the vision of decentralised digital fabrication and for the practical exploration of its possibilities. These processes of desiring, which are also imitations, foster experimentation when discursive strategies are used to make FabLabs desirable and to convince others to see and mobilise the possible in the present. This produces, enacts and transforms imaginations of why FabLabs are desirable and of how they can be mobilised. This is not simply done by ‘heroes’ such as Gershenfeld, but also on a mundane level in FabLabs. And it is the unfolding of the FabLab assemblage in total which provides ‘proof’ and visibility and sites for engagement in such explorations of the possible that different FabLabs afford. From this point of view, the history of FabLabs can also be read as a history of the ‘opening’ and diffusion of technoscientific practices through the spread and increasing publicness of experimentations with digital fabrication which was also produced by FabLabs.

What have FabLabs in particular contributed to the TechKnowledgy of open digital fabrication? Just as digital fabrication machines combine digital and material technologies, FabLabs combine ‘digital’ and ‘material’ forms of organising knowledge, which is, of course, also the organisation of people. FabLabs have been localised places for bodily engagement with digital fabrication technologies and particular forms of organising them, which are propelled by a dynamic to widen the audience of digital fabrication. This is a significant extension of the publics that are formed online based on explicit digitised knowledge and particular circulations thereof. FabLabs, inspired and empowered by such digital knowledge, have taken an ethos of openness into the material world and experiment with sharing knowledge through creating co-presences and circulations of digital machines, people and things. Particularly significant has been that FabLabs extended the common use of digital knowledge to the common use and organisation of material technical objects. Offering contact with digital fabrication machines, FabLabs are places to engage with these technical objects and with the tacit knowledge that is collectively held in the organisations. Thus, the relations to technical objects are embedded within relations to other people that are co-present. This spread to the material domain has not only provided novel points of access to digital knowledge commons but also enabled the intersection with other cultures and practices such as older forms of DIY or member-based organisations. Digital fabrication was, therefore, given a further significance as it was partly connected with already existing TechKnowledgies and creatively worked them into the TechKnowledgy of open digital fabrication, which is particularly condensed in most FabLabs.

What are the relationships between FabLabs, experimentation and the TechKnowledgy of open digital fabrication? The above-mentioned unity in diversity of the hundreds of FabLabs is striking. However, this also offers insights into the qualities of the TechKnowledgy of open digital fabrication. On the one hand, this TechKnowledgy through providing a vaguely defined set of procedures that aim to make digital fabrication public and to unfold it provided the coherence for the global spread of FabLabs. This is especially so as elements in these procedures, such as CNC machines, became increasingly accessible and the Internet spread knowledge about the procedures. On the other hand, through having been relatively flexible and not confined to particular goals or practices, these procedures proved to be very adaptable to local conditions and ambitions, and it has been this work of connecting to local contexts that has creatively unfolded FabLabs. The TechKnowledgy thus framed a problem, i.e. publicising digital fabrication, and offered particular procedures to solve it, e.g. through sharing knowledge online. FabLabs have turned this into the experimental problem of how to make digital fabrication machines locally accessible and contributed to finding ever more solutions to this problem in entwinement with other projects based on the TechKnowledgy. As the problem posed by FabLabs was increasingly taken up in local experiments, so other partial solutions emerged beyond FabLabs that could be integrated into experimentation, such as an increasing amount of open-source machines. This has also changed the problem increasingly into how to entwine digital and material aspects of open digital fabrication. Thus, in a recursive way the TechKnowledgy was itself the problem and the solution to experimentation through which it spread and transformed.

FabLabs are places where the TechKnowledgy of open digital fabrication is strongly present and so are its productive surpluses. Learning to participate in a FabLab also typically means learning to participate in the TechKnowledgy of open digital fabrication. Operating machines in a FabLab also means learning to act within an ‘open’ organisation and positioning oneself as a digitally empowered networked subject that explores digital machines and novel forms of the sharing of knowledge. As a subject you participate in one of these ‘laboratories’ of novel forms of organisations of material production and explore how you could co-become with the unfolding of the assembled technosocial procedures. The TechKnowledgy of open digital fabrication affects the becoming of people within its collective machines and FabLabs in particular bring the qualities and intensities of co-present interactions and collaborations into this process. In a profound sense open digital fabrication in FabLabs means acting and organising together with others to produce knowledge and technology. This entails action researchers as well, and I end this chapter with a brief reflection on my research experiment within the real-life experiment.

As I already discussed above, the FabLab Karlsruhe project started based on the creation of a shared desire for the lab and, as it was collectively brought into being, there was no prime agent in setting it up. In fact, this form of action research would not have been possible without partly myself becoming open digital fabrication together with the emerging lab. As the lab was set up within an aexisting global collective machine of open digital fabrication and many people familiar with it, there was clearly a collective pull that constrained individual powers to influence the process. This provides two important insights for action research. First, in such processes where expertise is spread and collectives experiment, the power of individual action researchers to determine outcomes is constrained. This, however, is a good thing and demands a particular attitude of becoming a co-experimenter instead of a designer of such processes. In an experimental attitude, action researchers search for the right questions and seek answers together with the other people who are acting. Second, this does not mean that action research is insignificant. Although FabLabs are widely spread and also relatively stabilised, they are not simply reproduced. There are spaces for novelty and action research can make a difference, especially as action researchers can bring a further knowledge culture into such collective processes and help to set up contacts to other institutions where professional scientific expertise is still an important control mechanism. I have been involved in applying for research grants involving the FabLab. In one successful case this enabled the building of the Lasersaur and several transdisciplinary workshops for reflections on digital knowledge. While arguably some people in the FabLab learned through this or were inspired by it, equally important was that my colleagues and I learned from such an experience. My engagement in action research was thus not only a way to have an impact on FabLab Karlsruhe but also a little experiment with reworking relationships of 'science' and 'society'. As open digital fabrication documents, novel publics that shape technology and knowledge are emerging, and if social science wants to co-experiment with them it needs to learn how to engage in a dialogue with them.

5 The opened future of digital fabrication

In light of the drastic societal changes through digitisation and technoscientification this study has developed analytics of TechKnowledgies and empirically investigated how open digital fabrication has been producing and organising knowledge and technology. This has also demonstrated how TechKnowledgies can be analysed in their unfolding and how such an integrative analytics that turns towards the entwined becoming of subjects, technical objects, desires and organisational forms is necessary to understand the recent reconfigurations of knowledge and technology due to digitisation and technoscientification. It has been shown how different elements that have entwined to form and influence open digital fabrication have been in the making for decades. For example, an ethos of openness has developed based on a digital utopianism from the 1960s onwards, put into technological practice in the 1980s in free software, and unfolded and transformed through 'open' projects in technology, arts, science and even government. Today, an ethos of openness is being enacted in various fields of practice that aim, for different reasons, to make digitised explicit knowledge public and often modifiable. An ethos of openness is fostered and stabilised through different, mostly digital, capabilities and their unfolding to produce and publicly circulate digital explicit knowledge. Similarly, this study claimed that the future of digital fabrication has been 'opening'. It has shown, however, how this opening has not been a simple linear process of ever more 'openness' that will simply go on.

By focusing on concrete productions and organisations of knowledge and technology and opting for a time-sensitive perspective on becoming, however, the analysis has shown that although the possibilities for open digital fabrication have been unfolding, there are also influential constraints on it. There is no certain future for open digital fabrication that can be predicted, although this is often claimed by practitioners and observers of it. For example, Neil Gershenfeld, who has been analysed as an influential visioneer in open digital fabrication, claims: 'It [digital fabrication] is an evolving suite of capabilities to turn data into things and things into data. Many years of research remain to complete this vision, but the revolution is already well under way. The collective challenge is to answer the central question it poses: How will we live, learn, work, and play when anyone can make anything, anywhere?' (Gershenfeld, 2012, p. 57). In the last sentence, Gershenfeld evokes a utopia of complete 'openness', with magical technical powers for everyone and claims that this will be the case in the future.

Instead of simply following such deterministic claims, I have shown how open digital fabrication has been produced and organised by particular people that make use of particular technical objects, organisational forms and desires at particular places and how each of these has been becoming to enable the collective conversions of data and things. I have documented and analysed the complex, labour-intensive, challenging, yet also motivating and empowering procedures that are necessary to produce and organise open digital fabrication. This has been a shift from descriptions and imaginations of the future to processes of future-making in a complex and unfolding present of open digital fabrication. While some practitioners certainly believe to be part of an ongoing revolution in manufacturing, this study has shown how such beliefs are part of the collective machine of open digital fabrication, where not everything is simply revolutionary but some things are rather tedious and constrained. Nonetheless, the past decade has bifurcated digital fabrication and opened a path of 'openness', next to the industrial path of digital fabrication that already emerged after the Second World War. This bifurcation can indeed be seen as a small 'revolution'.

5.1 The TechKnowledgy of open digital fabrication

Open digital fabrication, however, not only brought these technical processes beyond industry but has established a TechKnowledgy, a set of collective procedures that produce and organise technology and knowledge that is still in the making. In fact, as I showed, it has changed a lot during the past ten to fifteen years. Open digital fabrication was formed over decades because shades of Internet utopianism, technoscientific aspirations, ideas of nanotechnology, such as shaping matter through manipulating small elements, open-source projects, DIY cultures, digital platforms and more have been configured into particular collective machines that provided procedures for unfolding technology and knowledge as open digital fabrication. If we abstract these procedures from their concrete collective machines, the following comes into view as a condensed version of the TechKnowledgy of open digital fabrication as distilled from the analysed cases. This is an ideal type that is never fully realised, yet also never simply reproduced: TechKnowledgies create an overflow, a surplus in the processes in which they are realised. These procedures apply to subjects and organisations as well as to the forms of relations that are being desired or realised between people and technical objects. They are not only discursive, but are inscribed and embedded in the collective machines of open digital fabrication.

Desire digital fabrication machines! Believe that computer numerically controlled machines are manifestations of a powerful and still unfolding set of technical processes that make matter increasingly digitally malleable. Desire digital transformations of the material object world beyond what manual work typically could do. As the powers to shape digital information are diffusing, so too are these machines windows into a future in which many people could shape matter through shaping digital information. Therefore, share your desires and make others desire as well.

Digitise knowledge! Feel that open digital fabrication is a powerful way to entwine digital information, material settings and embodied knowledge. Look for and explore ways to digitise matter and to materialise digits. Any object and process that facilitates this could be useful. Correspond with digital streams of information and the technoecologies in which they circulate.

Become open! Be convinced that digital fabrication thrives if there are many points to access and to influence its streams of information. Access these; search online and elsewhere for knowledge and inspiration. Influence these; produce and circulate knowledge in co-presence with others and as explicit knowledge online. Create environments that enable a constant influx of 'information' in the form of technical objects and subjects. Participate in these environments and reach out to others to do so as well.

Project! Produce and engage in projects that put the capabilities and potentials of open digital fabrication into concrete manifestations. Develop and build a machine, design a form, produce an object, give a course, organise a FabLab. If the TechKnowledgy of open digital fabrication was the grammar, projects would be the words – speak and others will communicate with you.

Become open digital fabrication! Engage in the becoming of open digital fabrication yourself, engage in the becoming open digital fabrication of yourself.

These abstract procedures, however, do not exist in a void but are enabled and constrained by the concrete collective machines through which they are differently realised. A TechKnowledgy structures possible connections and intersections or prevents these; in a way it selects 'modules', e.g. objects, subjects, organisations, for the constitution of machines. The unfolding and future transformations of open digital fabrication depend on both the TechKnowledgy and the collective machines. As I have shown in the case studies, the TechKnowledgy of open digital fabrication and its collective machines are dynamically open to their environment and connect with other machines and interrupt flows. By now there are many different collective machines based on the TechKnowledgy of open digital fabrication that nonetheless afford particular relations and co-operations with each other and together co-define and unfold the spaces of possibility of the TechKnowledgy. These relate to each other in an ecological or environmental (cf. Hörl, 2013a) manner, not neatly integrated but forming a kind of changing landscape of desires, technical objects, organisational forms and subjects through which practitioners of open digital fabrication navigate. Importantly, this entails influences from other TechKnowledgies and corresponding collective machines as well. The TechKnowledgy of open digital fabrication, however, structures and guides particular ways through this landscape, particular paths into the future. In the collective machines they are differently followed in processes that create surprise, deviations and sometimes change that might also impact on the TechKnowledgy, if a change is widely imitated. A collective machine might flow away from the TechKnowledgy, such as when a FabLab hosts digital machines but no longer organises them 'openly'. Otherwise, new collective machines might emerge or become through transformations of others that entwine with the TechKnowledgy and influence its set of procedures – such as when grassroots FabLabs appeared.

While the TechKnowledgy of open digital fabrication is a powerful and collectively shared process, the contestations for its futures are taking place in the collective machines in which it was and will be realised by particular people at particular times and particular places. The ways in which these become open digital fabrication and parts of its collective machines is highly significant. That many people across the globe have been doing so has been enabled by a particular sense of contingency of technology and knowledge that is product and producer of the TechKnowledgy of open digital fabrication. Certainly, a culture of contingency is central to modernity, knowing that things change and that they could and will be otherwise in the future (Berman, 2010; Adam and Groves, 2007). But the TechKnowledgy of open digital fabrication itself has been installing a particular sense of the contingency of knowledge and technology that is put into practice. Within open digital fabrication knowledge and technology are being perceived, desired and practised as malleable beyond dominant institutions and TechKnowledgies. Not only is the constructed nature – and, therefore, the contingency – of knowledge and technology brought to the forefront, but the construction process as well. The TechKnowledgy of open digital fabrication has been entwined with and itself producing particular procedures to foster and guide such construction processes to enable particular becomings of technical objects, subjects, desires and organisational forms.

Through this, it has been producing an ontology of knowledge and technology that entails highly dynamic and mostly digitally mediated correspondences between people and digital machines. Central to this ontology is that the production and access to technical objects is widely distributed amongst different individuals who co-operate within and with vast informational networks and respective arrangements that seek to foster such co-operations. Digital and material forms are considered equally malleable and, therefore, restrictions of technical transformations are sought to be overcome, as material objects and forms of organisation are increasingly construed and practised in light of the fluidity and mobility of digital objects. As such, access to technical becoming is becoming available and visible. The ontology of open digital fabrication for its practitioners corresponds with the tendencies of an unfolding digital and technoscientific age that turn decades-old dominances of other TechKnowledgies into equally contingent formations. It is this making different, this making contingent of knowledge and technology, that has been at the heart of open digital fabrication and created collective machines which, through their practical experimentations, have 'opened' the future of digital fabrication. Digital fabrication and its further becoming is now possible beyond industry, albeit without a neat and dichotomous separation between these paths but complex machinic becomings and partial intersections. As the world seems to be increasingly 'fabricated' as 'open' and 'digital', open digital fabrication occupies a central place for contested experiments in shaping the becoming of technology and knowledge.

The future of any TechKnowledgy, however, depends upon historically emergent ecologies of people, objects, organisations, infrastructures, economies and cultures and other TechKnowledgies that foster or hinder particular entwinements and becomings. Given such inherent complexities, it is impossible to deterministically provide pictures of how open digital fabrication will look in the future. However, one can at least try to explore spaces of possibility, formed by its current tendencies that give a sense of the 'near future' (cf. Rabinow and Bennett, 2012) of open digital fabrication. What are the forms of stabilisation and possible transformations of open digital fabrication in relation to technical objects, subjects, organisational forms and desires in dynamic collective machines?

The *technical objects* of open digital fabrication are fundamental to its collective machines. In an object-historical reading, open digital fabrication was born out of the intersection of the Internet and personal computers on the one hand and the decreasing size and increasing affordability and accessibility of digital fabrication machines on the other. The former constitutes an unfolding network for the manipulation and circulation of digital information and the latter a set of machines that intervene in matter based on digital instructions. The TechKnowledgy has been based on efforts to make the production and organisation of digital explicit knowledge more public and ways to conceive of and manipulate material objects through digital information. In its collective machines it draws upon procedures to produce and organise information and material objects and to produce or transform technical objects to do so. Its further unfolding will be influenced by changes and advances in the technical capabilities, as important elements in respective procedures, to produce and circulate digital explicit knowledge and to digitally intervene in matter. Various kinds of new design software or Internet-based communication systems, for example, are likely to be taken up by open digital fabrication. Digital fabrication will not necessarily remain restricted to laser cutting, milling or 3D printing, as for example technical objects to digitally intervene in genes and biological organisms already exist and a growing sphere of DIY biotechnology enthusiasts are working on open sourcing synthetic biology and other forms of biotechnology. Especially important, however, will also be the technosocial and politico-economic question of accessibility and distribution of these capabilities amongst people and organisations. It needs to be remembered that industrial markets for digital fabrication machines have existed and even enabled open digital fabrication, e.g. at MIT. By and large, however, open digital fabrication could remain rather stable in its technical capabilities if technoscientific advances continue to remain scarce through intellectual property regimes or if significant technical advances in open-source projects that develop machines fail to materialise and prices for capable machines remain high.

The *subjects* of open digital fabrication are not a homogeneous group, yet they are also not the often heralded 'everyone' that is said to be digitally empowered. Although the figure of the maker emerged in close entwinement with it, this has been a flexible figure and not the only one that takes part in open digital fabrication. Therefore, it is more fruitful to not think about figures or identities but about subjects whose becoming entwines to greater or lesser extent with open digital fabrication. As I argued, these subjects, professional and non-professional alike, become with open digital fabrication, correspond with it, learn its procedures and unfold it and themselves in particular ways. They are subjects who position themselves within the collective machines that afford such positionings. In Karlsruhe and elsewhere, there have been efforts to reach out to groups, e.g. school children, beyond regular users of the lab who might strongly identify with open digital fabrication. There might, thus, be a widening of the social base of open digital fabrication and a further diversification of the practices and aims associated with it. The becoming of subjects with open digital fabrication, however, also depends on the capabilities, usability and accessibility of its procedures, that together configure particular forms of expertise, including technical and social skills, which have exclusionary effects. Becoming with open digital fabrication takes time and effort and is related to questions of a possible professionalisation or other politico-economic changes that make time and resources available to people who engage with it. If these do not take place, open digital fabrication is likely to remain mainly based upon people who strongly identify with it and use time outside of education and work to engage with it, for example hobbyists.

Especially *organisational forms* have been important for the ‘openness’ in open digital fabrication. Both case studies analysed how different individual organisations and organisational forms are being used and various co-operations are established in the formation of collective machines and their heterogeneous flows. Therefore, it is not fruitful to construe open digital fabrication along one central organisational trait in dichotomous forms as either for or not for profit or as hierarchical or heterarchical, for example. As ‘openness’ is being put into different constellations that sometimes emphasise public explicit knowledge, access, inclusion or collaboration amongst particular groups in a rather pragmatic manner are organisational forms being deployed. This entails forms of ‘online’ and ‘offline’ organisation as well as different forms of their entwinement. Open digital fabrication is not restricted to open-source collaboration projects online but has entailed other ‘networked’ forms of organisation that sometimes mix markets and public knowledge or provide various forms to access and to produce public information concerning digital fabrication, for example crowdfunding platforms or platforms for the free sharing and selling of digital templates. As digital capitalism increasingly turns towards the ‘platform’ as business model (Srnicek, 2016; Morozov, 2015), more services might appear that connect individuals and organisations involved in digital fabrication that are likely to compete with other, non-commercial forms of online networking. Open digital fabrication, however, needs the bodily engagement with the machines and this entails individual and common forms of ownership and usage. Particularly in cases where organisations provide the machines, there exists a plurality of organisational forms and economic models that are in some cases contested. This plurality might split open digital fabrication into more product-oriented and more education- and learning-oriented organisations. It might also be that novel organisations appear that become influential in open digital fabrication’s further becoming – just as the emergence of grassroots FabLabs proved to be.

Open digital fabrication has been differently *desired* and most likely will continue to be part of different conceptions of desirable futures. Particularly influential, however, have been technoscientifically inspired desires for digital fabrication machines. It is an open question as to whether many people will continue or start desiring machines such as 3D printers or laser cutters, especially if the accessible forms of these machines do not significantly progress in their capabilities or applications. However, within open digital fabrication, creative uses and changes in the organisational contexts of these machines have also been desired. Such desires for ‘openness’ have been very influential in efforts to publicise open digital fabrication. This has entailed desires to provide new ecologies for start-ups as well as non-commercial forms of collaboration and inclusion. In a more general sense, this has been a desire to transgress established institutions and differentiations, a desire to make the becoming of digital technologies increasingly accessible. As ‘openness’, however, is increasingly diffusing and practised in very different manners so too is it connected to other desires. Which intersections of different desires are created depends on the collective machines to which they are connected. Which practised and performed desires can gain further support, e.g. by municipalities, larger companies or even governments: education in technology, a renewal of industrial practices, the reconfiguration of local economies, participatory forms of technoscientific research, post-capitalism or something else? The desires that are connected to open digital fabrication, as its other aspects, circulate within environments that are currently highly dynamic.

Individually, however, each of these tendencies might remain marginal for open digital fabrication. Yet if several of these and maybe others add up to significant combinations and widely shared procedures, there might be surprising machinic change. It is, however, the architecture and character of the concrete collective machines of open digital fabrication in each instance that defines the qualities of what open digital fabrication is to particular people. Furthermore, as I discuss below, open digital fabrication is but one field where TechKnowledgies are being transformed currently.

5.2 Into an age of contested TechKnowledgies

The TechKnowledgy of open digital fabrication has been emerging within a highly dynamic society in which questions of knowledge and technology are increasingly at the forefront of societal contestations and transformations. Especially the entwined processes of digitisation and technoscientification are creating transformations that open up contested spaces and different possibilities for the becoming of technology and knowledge and, thus, of people and socialities. As novel technical capabilities and prototypical arrangements are increasingly circulating and diffusing, partly out of control, all kinds of real-life experiments with these are being conducted. In the following I explore such spaces and argue that we can learn a lot about them through open digital fabrication, as TechKnowledgies are no longer taken for granted.

Digitisation has been increasingly turning towards the material world. No longer is digitisation a question of connecting personal computers; instead material objects, environments and infrastructures are increasingly made digital. The visions of an ‘Internet of things’ (e.g. Rifkin, 2014), of ‘smart’ x or y (e.g. Lösch and Schneider, 2016) or ‘industry 4.0’ (e.g. Pfeiffer, 2016) have gained traction to denote different aspects of such an unfolding world in which material and digital flows are ever more tightly connected or at least desired to become so. Ontologically, this forms a world in which material aspects become progressively malleable through digital technologies. Informing matter and material processes is then also a process of producing and circulating digital information. As potentially dramatic changes are under way in the constitution of material environments questions are arising as to who can influence these changes and how. Open digital fabrication has been one field for experimentation with the reconfiguration of such relationships that do not only concern digital and material objects but people and organisations as well. From a perspective on TechKnowledgies, ideas of an ‘Internet of things’ are insufficient to draw attention to the simultaneous arrangements of technical objects, organisational forms, subjects and desires. Larger projects or strategies to digitise particular environments need to be scrutinised concerning how people and organisations are being made affordable for particular digitisations and how this affects their becoming. The political question as to who controls information, raised by open-source practices, therefore is no longer confined to ‘online’ worlds but with the spread of digitised material environments is becoming a central technopolitical question in all these environments. And it is fundamentally a question of TechKnowledgies.

In addition to these ongoing changes in the reconfigurations of technical object worlds, digitisation spurs dynamics of the reconfiguration of political economies as well. On the one hand, the project of ‘open’ knowledge is spreading and an ethos of openness is being practised in different forms and projects. Besides such often explicitly knowledge-political projects there are, on the other hand, an increasing amount of projects, services and organisations that draw upon and foster various collaborations or participations of people who are connected ‘online’. Some authors describe a rapid increase of ‘prosumers’ (Ritzer et al., 2012) to designate the blurring of consumption and production especially through digitised networks. However, the changing of roles and functions within political economies entails more than the reconfiguration of individual practices. Any area where patterns of consumption and production are fundamentally transformed faces transformations of TechKnowledgies.

In this unfolding digital age it seems likely that experimentations with dramatic reconfigurations of knowledge and technology are becoming increasingly widespread. The TechKnowledgies that have been stabilised over the 20th century need not necessarily remain that powerful, as TechKnowledgies are even contested between digital capital and industrial capital. It is highly indicative of the growing importance of changing and contested TechKnowledgies that the European Commission, for example, is proposing an agenda for ‘open innovation’ and ‘open science’ (European Commission and Directorate-General for Research and Innovation, 2016). Any changes, connections or emergences of TechKnowledgies, therefore, have to be seen as reconfigurations of political economies. Whilst some see the potential rise of post-capitalism due to growing forms of networked collaboration (Mason, 2015; Srnicek and Williams, 2015; Rifkin, 2014; Hardt and Negri, 2009), others herald a new boost for entrepreneurship and digitised markets (Anderson, 2012; Baldwin and von Hippel, 2009). However, instead of following claims about futures we ought to turn to the experiments in which TechKnowledgies are being reconfigured, such as open digital fabrication. Their constitution already lays the ground for becomings of political economies, as economic processes are an integral part of TechKnowledgies.

Deeply entwined with the dynamics sketched out above are processes of technoscientification. Whilst a range of scholars have turned towards futures and imaginaries to study the entwinement of technoscience and society it is time to turn towards technoscientific becomings of society, that is the TechKnowledgies that produce and organise technoscience as part of society. Open digital fabrication shows that not only are technoscientific imaginaries or products diffusing but even technoscientific practices such as the exploration of novel technical capabilities themselves. In fact, what many researchers on technoscience do not see so far are the growing possibilities and experiments of technoscience beyond established technoscientific institutions such as universities. Besides open digital fabrication, many experiments already take place that seek to at least alter established forms of technoscience. Not only in FabLabs but also in policy labs, living labs or other forms of 'labs' in society are different forms of participation in technoscience being experimented with. The EU governance on 'Responsible Research and Innovation', which seeks to involve citizens and a plurality of actors into the definition of the aims of technical innovation, and trends towards participatory design practices are trying to change the aims and practices by which technologies are being shaped. Whilst the above designate very different fields of practice what they share in common is that they all imply transformations of TechKnowledgies. And they indicate that possibilities for the becoming of technoscience are emerging that might significantly alter its formations. As a paradox effect of the technoscientific imperative to technologically design the world (Nordmann, 2016), alternatives to the settled forms of technoscience might be 'designed' into being through collective experiments with TechKnowledgies.

For such reconfigurations of TechKnowledgies technical objects, their formation in networks and distributions are highly significant. Technoscientific practices depend upon unfolding and not fully determined objects and the related ontologies. As a growing amount of technical objects and products of technoscience become digitally connectable their potential uptake in digitised collective machines of knowledge production becomes possible. However, it is not guaranteed. Seen from TechKnowledgies, a growing and indeterminate network of technical objects can face strategies to confine technical becoming and to create exclusionary processes. On the other hand, we have seen how there are strategies to enable accessible forms of technical becoming. Technical becoming, so central to technoscientification, whether in its high-tech Silicon Valley shades or in grassroots organisations, is, however, also about human becoming and a possible exploration of forms of life. And there are growing signs that many pathways, however powerful until now, have opened for this.

In this unfolding age where technical and human becoming are so tightly fused and are based upon extraordinary dynamics, TechKnowledgies are the key procedures that organise these dynamics. For research TechKnowledgies provides a concept to extend the relational thinking and analysis of technological phenomena. When thinking in TechKnowledgies, the guiding difference is not that between technical artefacts and people and socialities but that between different collective procedures that unfold technology and knowledge differently. Evidently, in TechKnowledgies heterogeneous elements are entwined within procedures, yet the key is to put the emphasis on the particular ways in which they are connected and unfolded, what different functions they have and how their co-becoming is mediated. TechKnowledgies focus on the qualitative differences, on different techno-*logies* and on their related ontologies that make 'knowledge' and 'technology' differently. If we better understand how elements are being made affordable for particular connections and how this creates emergent dynamics, we can gain a better understanding of collective design processes that shape not only technical artefacts but also forms of life.

The concept TechKnowledgies is, therefore, also a way to go beyond the still powerful distinctions and traditions of 'structural' and 'micro and situational' analysis. Whilst much of STS research on 'material semiotics' and ANT has shown in many micro studies the fine details and situations of entwining technical objects and knowledge, TechKnowledgy emphasises the historically emergent collective procedures beyond concrete situations that enable and constrain particular entanglements in situations. This is rooted in the time- and process-sensitive perspective on becoming that is neither simply about a deterministic reproduction of structures nor about a pure contingency and creativity of situations. TechKnowledgy is a way forward in times when it is highly unclear what 'technology' in general is. Rather, by focusing on TechKnowledgies we may come to understand that each TechKnowledgy forms a particular version of 'technology'. TechKnowledgy as a non-reductionist concept locates 'technology' not only in technical artefacts, not only in discourse, not only in acting subjects and not only in organisations. Instead, by following the perspective of TechKnowledgies we can come to see 'technology' as a complex and dynamic process made up of heterogeneous elements and the surpluses that their connections create. TechKnowledgies instruct processes that enable and constrain the ways in which technosocial worlds are made and can be remade. Power in an age of technoscientification and digitisation operates through the TechKnowledgies that make particular forms of the entwined becoming of technical objects, people, desires and organisational forms possible or impossible. TechKnowledgies can potentially be influenced through transforming any of these and through connections with other TechKnowledgies. Better understanding TechKnowledgies will help us better understand the forces that shape our technosocial worlds and ways to transform these.

The point about TechKnowledgies is that they provide the procedures to produce and organise knowledge and technology and to regulate who can do this under which circumstances. As some of the recent TechKnowledgies, such as open digital fabrication, are still unsettled and unfolding in many ways, they provide opportunities to interfere in them and their becoming. A growing number of people and organisations are doing so. And, as should be overly clear by now, any TechKnowledgy entails many ways in which 'social' arrangements are reconfigured or afford reconfigurations. Accordingly, there is room for an engaged 'sociological imagination' in experiments with still unsettled and dynamic TechKnowledgies. STS scholars are increasingly acknowledging that their research is making and re-making worlds. Yet, as the technoscientific rationality is becoming dominant, we need ways to reflexively engage with it and the novel publics that are based upon such rationalities; a TechKnowledgy in the making is a huge opportunity for that. Phenomena like open digital fabrication invite engaged researchers to rethink their own practices and to contribute to experimentations and contestations of TechKnowledgies.

TechKnowledgies, however, are not only made of discourse and theoretical discussions. Rather, to engage with TechKnowledgies we need to work with particular people at particular places and times. There is no guarantee but engaged and inventive research might influence the becoming of collective machines and engender changes that are taken up beyond these. Such engagement, however, is never in a void, but it has to partly become with the TechKnowledgy and partly adhere to its procedures to be able to meaningfully connect. Of course, this does not leave scholarly practice on a clean and neutral spot. However, even deeply held convictions by some researchers, such as 'neutrality', can be seen as being constituted by a TechKnowledgy if the research tries to have an effect on technology in society. Many arrangements such as the parliamentary technology assessment, which advises parliaments, or forms of social science in Responsible Research and Innovation projects can indeed be seen as involved in TechKnowledgies. Creative researchers in engaged forms of STS and in technology assessment might, therefore, not only start to influence TechKnowledgies but to transform the TechKnowledgies within which their own professional practices take place, if they are willing to experiment beyond their own routines.

The TechKnowledgy of open digital fabrication, however, reminds us that TechKnowledgies cannot simply be constructed on purpose – a fact that can be seen as frustrating or empowering. Many things have to come together over a process that can take decades for a successful TechKnowledgy that spreads beyond individual instances. Such spreading, however, can be as drastically creative and surprising as it can be ambivalent. Whilst TechKnowledgies structure becomings, there is an inherent variability to them and the collective machines that they form. Nonetheless, within open digital fabrication we can find particular examples of collective machines that encourage us to imagine and to practise becomings that point in as of yet uncertain directions of democratisations of technology and knowledge. If we want to foster similar trajectories, then transforming TechKnowledgies is our collective task.

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What people know about technology is drastically changing. Through digitisation and technoscience technical capabilities are proliferating and the meanings and contexts of ‘technology’ are transforming. This study analyses a field where novel digital capabilities and hopes for social transformation have merged to form arrangements that seek to democratise knowledge and technology through collaboration. In ‘open digital fabrication’ people and organisations across the globe have developed and used digital machines such as 3D printers and laser cutters, shared knowledge about them and created arrangements for their common use. In FabLabs and on digital platforms, but always in entanglement with technical objects, ‘makers’, developers, enthusiasts, scholars and tinkerers have transformed digital fabrication and opened it up to networked and participatory processes. Through digitisation machines but also knowledge and socialities have become malleable in new ways. This book shows how we can understand the new TechKnowledgies, the dynamic sets of collective procedures that produce and organise technology and knowledge that redefine the entanglement of our society and its technologies.

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