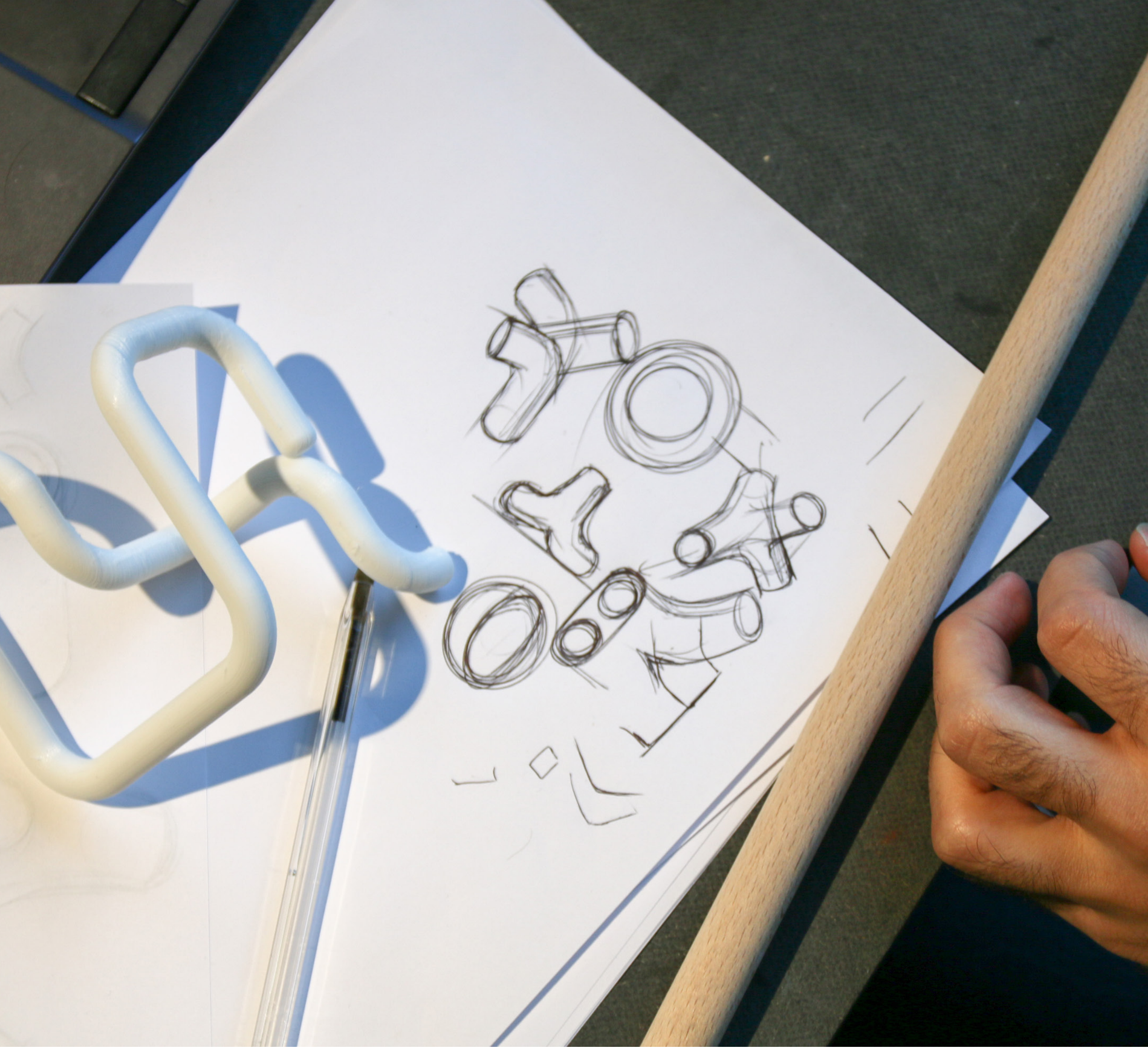

William Lavatelli Kempton

UNPACKING MAKING

A Product Design Critique on Emergent Uses of Additive Manufacturing

AHO Arkitektur- og designhøgskolen i Oslo
The Oslo School of Architecture and Design

PhD Thesis

William Lavatelli Kempton

UNPACKING MAKING: A PRODUCT DESIGN CRITIQUE ON EMERGENT USES OF ADDITIVE MANUFACTURING

CONTENTS

ABSTRACT

In recent decades, designers have applied 3D printers as Rapid Prototyping (RP) tools for developing design ideas. Today, as technical capabilities are advancing, these tools are finding newfound uses within design practice as an Additive Manufacturing (AM) technology. Similarly, technical advances are shifting AM towards consumer use. This thesis sees a need to compliment technical capabilities of AM such as customisability, enhancement and computation through a research by design based inquiry located in product design. Through such a practice-led mode of research, it argues that AM needs to be supported by critical reflection of its technical capacities, as they are subjected to interpretation through contexts of use.

In the context of product design, the project of the thesis is to tackle this need for sociotechnical perspectives in AM. It does so through investigating the relationship between design, making and critique. As the title suggests, unpacking making plays a central role in accessing topics of research, through its engagement with practice and in generating knowledge. These research topics cover the emergence of AM, product design expertise and technological critique. The study applies methods and processes from within design and making to generate knowledge around the emergence and use of AM. I connect this emergent use to my own constructive design practices, where I have developed novel 3D printing processes, as well as through observing expert- and prospective design-practitioners. This mode of inquiry is supported by critical design approaches, such as critical making. Together they situate the study within design pedagogy and critique.

In the mode of a thesis by compilation, I develop a holistic model of design-making critique in which product design is oriented towards critical and future-oriented forms of inquiry. With making as a core and integrating activity, the model moves from design-making critique through emergent use groups, into a wider technological design frame. The model is positioned with respect to the diverse means, context, tools and memberships in which making is made manifest. The model has the potential to contribute to design practice as a tool for technological reflection.

The study makes the following overarching contributions. Firstly, it critiques the sociotechnical transformation of AM from within the product design field. Secondly, it incorporates theories of socio-technological development into design pedagogy. Thirdly, it realigns critical making approaches to design expertise. For design practitioners, the study may also be useful for generating insight into the technical materials of AM, and in applying them in contextual design processes.

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1 Introduction

1.1 Summary of the study

In the past 15 years, attention in digital fabrication technology has increased within industry and research, and in popular imagination (Ratto & Ree, 2012). As a technology that encompasses additive and subtractive manufacturing methods, digital fabrication technology is capable of transforming digital form into physical shape. AM in particular, formerly known as rapid prototyping (RP; Pham & Dimov, 2001) and colloquially known as 3D printing (Kempton, 2017a), is pursued in wide-ranging domains. Additionally, owing to its layer-based manner of fabricating artefacts, AM is discussed within design and engineering in terms of its customisable and enhancive capacities (Campbell et al., 2012). These capacities are typically tied to related fields of interest, such as design optimisation (Doubrovski, 2016), rapid manufacturing (Hopkinson et al., 2006) and self-assembly (Tibbits, 2017).

In parallel with such developments, an increasing amount of research is brought to the social capacities of AM. Topics include open design and prosumption (Hermans, 2015; von Hippel, 2016), socioeconomic change (Ratto & Ree, 2012) and myriad political orientations including the relocation of goods manufacture (J. Stein, 2017).

This study shifts attention from a predominant focus on the material outcomes and characteristics of AM into the field of product design (Killi, 2013). The product design field is itself in transition, as human-computer-interaction (HCI), interaction design (Löwgren & Stolterman, 2004) and service design cultures (Meroni & Sangiorgi, 2011) shift their attention towards the design of immaterial products and technologies, while embracing multi-disciplinary and co-participative approaches (E. Sanders & Stappers, 2008). Product design, which traces its roots to a tactile, material and craft practice (McCullough, 1998), can act as a critical medium for

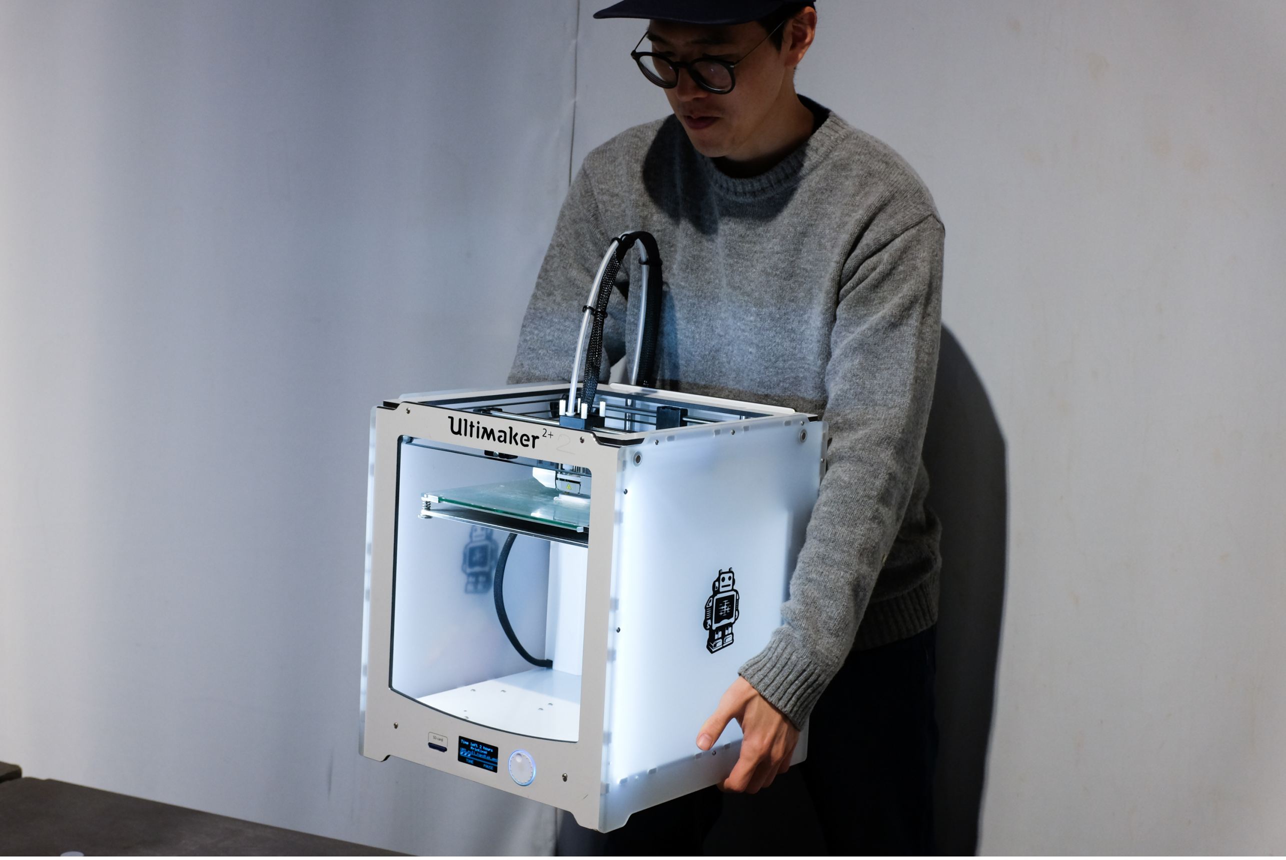

Figure 1 –3D printers are made available to new audiences through its portable, desktop-friendly format. Here, a student designer moves a Ultimaker desktop 3D printer as it continues to fabricate parts for a temporary exhibition. Photo: William Kempton.

reflecting on cultural, social and ethical values of technologies such as AM (Dunne, 1999). Its ability as an applied practice to engage with, realise and form technology is a crucial step in reflecting on the very same technology. At the same time, it arguably needs to position its approach to technological critique by realigning the practice of making objects to building knowledge.

In this study, I offer a way in which to situate design practice for understanding emerging sociotechnological phenomena with respect to product design. Phenomena such as personal fabrication, which is made possible by portable, desktop-friendly 3D printers such as the one pictured in Figure 1. I take up an approach which combines designerly inquiry, including interest in people, products and processes of knowing and making, with perspectives from academic interests in Science and Technology Studies (STS; Akrich, 1992; Bijker, 1997; Feenberg & Callon, 2010; Ihde, 2008; Leonardi, 2012; Suchman, 2007). Specifically in the context of product design, I seek to understand the relationships between design, making and critique in emergent uses of AM.

This study of AM's emergent use is a growing field of technical research which involves the novel process of joining materials using computational tools to create freeform, physical objects. AM, and in extension 3D printing, is subject to much speculation and anticipation in relation to its perceived social uses and practices (Birtchnell & Urry, 2016). Assuming that such a social uptake is a vital part of any technological development, I argue that design plays a valuable role in unpacking the status of AM as a potential everyday phenomenon. This form of unpacking is strongly related to the notion of emergence, which can be understood as the temporal settling of relations between human agents and material agency. As Pickering (2010) states, emergence is in essence 'a sense of brute chance, happening in time - and it is offensive to some deeply ingrained patterns of thought (2010, p. 24)

To set the stage for this design-oriented research study, I first discuss ways in which product design may position itself towards a critique of sociotechnical change (DiSalvo, 2014; Dunne, 1999; Ratto & Ree, 2012). To date, such critiques are taken up in different ways. For example, a critical design may speculate on future scenarios through making discursive artefacts which communicate alternative ways of being. A design may also forward a critique through the materialisation of abstract, theoretical concepts (Ratto, 2011). Here, *critique* is viewed as the methodical use of material artefacts to question and reflect on the societal impact of technology. While such critical making and design practices bring together design methods and technological inquiry in novel ways, little attention is placed in drawing analyses on AM through designed artefacts, using theories of sociotechnical development. I argue that such a focus provides valuable insight because, at present, AM is still predominantly subject to technical discussions (Conner et al., 2014). This emphasis is also evident through the term (AM), which is heavily oriented towards mass-production, and therefore also industry, feasibility and financial gain.

At the same time, emergent uses of AM are speculative, explorative and conceptual. In addition to a blossoming attention in diverse areas such as biomedicine (Li et al., 2016) and digital gastronomy (Zoran & Coelho, 2011), collaborative and open-source projects provide novel agendas for AM and 3D printing. Projects, such as E-Nable, combine artisanal sensibility and digital fabrication tools to build user communities through facilitating, fabricating and distributing low-cost prosthetics (Bennett et al., 2016). Such emergent uses provide an important aspect of sociotechnical development because they interpret 3D printers and AM technologies according to their subjective needs and interpretations.

Therefore, through a critically oriented design perspective, I aim to address the perceived gap between the technical developments and situated uses of AM. In other words, this study discusses the development of AM as one which is affected by broad technical advances underway, as well as in individual interpretations of its use.

1.2 AM technologies

Having addressed the need to extend the technological uptake of AM into product design, attention is oriented towards established and emergent uses of AM. In the following introductory unpacking of the term AM, I locate its use within engineering sciences, while pointing towards emergent interests.

The arrival of the first commercial layer-based digital fabrication tools[1] in 1989 were made possible by advances in the application of Computer-Aided Drawing (CAD) within design and engineering disciplines (Kochan, 1993). Within a reasonably short period, many of the processes still used today, such as Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS), were developed. Until the early 2000s, RP remained the dominant framing for 3D printing within design, engineering and architecture. This is because its use was principally tied to expert development processes (Hague, 2006). While *rapid* referred to the ability to create models quickly, *prototyping* related to the process of making articulations, manifestations and visual design representations of an idea or design concept. RP is here seen for its ability to augment to-be artefacts, so that participants could experience and record instances of its uses (Verlinden et al., 2009).

At the turn of the millennium, AM started to find commercial uses within niche markets, such as tailored hearing instruments (Masters, 2002) and for detachable dental aligners (Wohlers, 2010). Following developments such as these, the discourse around RP & AM increasingly turned beyond the vision of fabricating prototypes, which is often seen as taking place behind the closed doors of a workshop environment. Edited collections such as *Rapid Manufacturing: An Industrial Revolution for the Digital Age* (Hopkinson et al., 2006) outlined a series of industrial applications for 3D printers as manufacturing technique. The framing of rapid *manufacturing*, as opposed to prototyping, emphasises how 3D printing artefacts and processes have

[1] For a thorough review of AM fabrication processes, I refer to the appendix in the second publication, titled *A Design Sociotechnical Making of 3D Printing* (W. Kempton, 2017a).

Figure 2 – Top: Bre Pettis, founder of Makerbot, presenting the Makerbot Replicator made from a lasercut, wooden chassis. The image caption in a promotional video from 2012, shows Brettis presenting the 3D printer's new dual extruder capabilities by printing a coloured globe (Makerbot, 2012).
Bottom: The promotional video of the most recent Makerbot, the Method, presents a different image. The 3D printer, which is now cladded with injection moulded plastic parts on top of a steel chassis, is now situated in what appears to be an office or workshop. The 3D printer, which also sports a dual extruder, is now used for making support structures on an unspecified product prototype (Makerbot, 2018). Photo: Makerbot (2012; 2018).

matured to include end-use. Soon thereafter, the term *Additive Manufacturing* started being taken up among those professionally applying the tool, and as a standardised term for the 'process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies' (ISO/ASTM, 2015). The foundation of new academic journals since 2014, such as *Additive Manufacturing,* aim to advance and incorporate research in diverse field such as 'design and modelling', 'additive manufacturing processes', 'multiple and novel materials', and 'special applications' such as medical (Ozbolat, 2017) or robotic applications (Frketic et al., 2017).

1.2.1 Between AM and 3D printing

While the industrialised application of additive digital fabrication techniques continue to be discussed under the banner of *additive manufacturing,* adjacent terms continue to thrive. In particular, *3D printing* has come to represent a mode of application which relates more heavily towards the social contextualisation of the particular technology (Lupton, 2018). 3D printing has become synonymous with personal fabrication (Mota, 2011), which is made popular by consumer-oriented tools such as MakerBot (Figure 2) and Ultimaker, online repositories such as Thingiverse, Instructables, Youmagine and Defence Distributed, and a plethora of easy-to-use CAD applications. Demarked by the release of crucial patents in 2009 (Crump, 1992), 3D printers are increasingly found within university campuses, makerspaces and in public libraries. While its uses may inspire renewed interest in *digital literacy* (Gershenfeld, 2008), particularly for educational purposes (Blikstein, 2013), its uses are arguably a far cry from the broader claims that are envisioned for AM. Figure 2 illustrates how the original Makerbot Replicator from 2012 was advertised as a household item capable of printing toys and other products such as miniature globes. More recent adverts for Makerbot, however, are less oriented on personal fabrication and home consumption. Its use is now situated in a prototyping environment which is a well-established use of the 3D printing tool. In doing so, it leads me to consider – what are the future uses of AM?

1.2.2 Additive as more than manufacturing

Reviewing both literature and use contexts of AM reveals an interpretation of its uses which is not confined to a single, established area of use. In the same way that a smartphone does more than merely call or text friends, the form in which AM appears is increasingly that of a platform for social disruption and change. Attempts at defining AM will undoubtedly produce varied accounts of its technological status. For engineers working within the specific areas such as topology optimisation, AM can be discussed on the premise of its capacity to integrate optimised topology within a structure (Zegard & Paulino, 2016). By contrast, AM can act as a building site for socio-political agendas, and it is thus discussed in terms of on-shoring and the economic revival of the nation state (J. Stein, 2017). It can also be seen as a platform for distributing online weapon blueprints by white supremacists (Fordyce, 2015).

As such, developing a research inquiry around AM's technological practice cannot solely be placed on its technical capacities. Rather, a research on AM technology must include attention to all aspects of its practice. This includes the cultural aspects (goals, values, creativity), organisational aspects (economic, professional & consumer activity) as well as the technical aspects (knowledge, skill, technique, tools) of technological practice (Pacey, 1983).

In other words, a critique and inquiry on AM must be seen in relation to all these technical, organisational and cultural practices. This includes attention both to the specific processes that go into fabrication, the techniques that apply to it, and the popular role it has in terms of belief in societal progress and environmental sustainability. It is therefore crucial, I argue, that AM is discussed in relation to a broader, culturally embedded version of technological practice (Slack & Wise, 2015). At the same time, the wording of the term *manufacturing* has a strong industrial affiliation because it leans into the manufacture of user goods and the subsequent consumption by end-users. How, then, can interest be oriented from investigating not only the technical capacities of AM? Is it possible through design to investigate the social capacities of AM, which might interpret on, and contribute to explore new practices on AM technology?

1.3 Research questions

The central issue is that there is little understanding of how a broader definition of AM technology is pursued from within product design research and development. Considering this lack of sociocultural interest, it is relevant to ask the following question: In the context of product design, what are the relationships between design, making and critique in emergent uses of AM?

More precisely, this question can be formulated as three separate sub-questions: What are the emergent uses of AM? How can these uses be unpacked through design expertise and analysis? Why is such a perspective relevant for a critique of AM's technological development?

These research questions address three areas of interest. The first research question highlights the need to identify the emergent and less apparent uses of AM. In doing so, it focuses the study on the diverse practices that are conducted using AM technologies, providing a starting point for which perspectives, utilities and critiques of AM can be brought. The second question, which asks how such a critique can be brought by design expertise and analysis, puts attention on the capacities of design practice and inquiry. In doing so, this question stresses the need for incorporating generative and

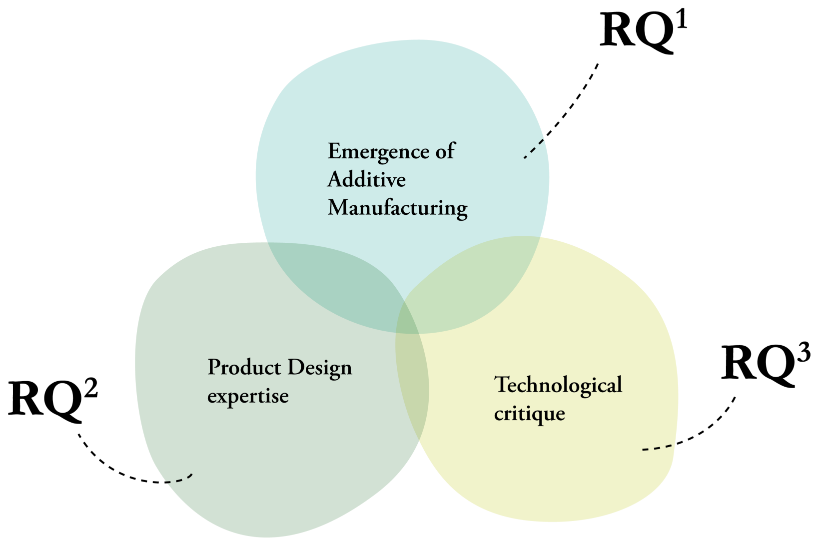

Figure 3 – Drawing a link between the research questions asked, and themes outlined for this exegesis. Illustration: William Kempton.

analytical design methods. The third question brings attention to the critical evaluation of the technological practices surrounding AM.

1.4 Outlining themes

The study can be discussed in relation to three principal themes. Each theme relates back to the identified research questions (Figure 3). The first theme (emergence of AM) relates to AM and its emergence in industrial and social contexts. As it has not yet achieved a status that is established through conventions and use, AM is understood differently across a wide spectrum of separate uses and applications. The second theme (product design expertise) centres on how this emergence is investigated using methods and practices of product design. The third theme (technological critique) is that of developing a critique on AM technology in which design inquiry brings together theories from critical literature on technology development.

1.4.1 Emergence of AM

Emergence can be understood as a process of unfolding. It happens over time and it may compliment or even conflict with existing patterns of use (Pickering, 2010). In relation to technological uptake and adoption, these processes may be illustrated through charts such as Gartner's hype cycle, where the term *3D printing* peaked in 2012 (Gartner Inc, 2012). The emergence of AM can also be understood as how AM is polarised by professional and layperson practices, such as design, entrepreneurship, business management and technical research.

To unpack and discuss technologies as *emergent*, it is therefore necessary to bring the *social* aspects (Bijker, 1997) of technological practice into discussion. In relation to AM, these social practices are still opaque because the technology is continuously reinterpreted among its users. Apart from having different working theories about what AM *is* and what the technology *does* (see publication 2 for an analysis of relevant user groups to AM), their methods for engaging with AM technology vary. As such, research on AM is brought up vastly different subjects, from new concepts for value creation such as open innovation (Chesbrough, 2003) and peer-production (Troxler, 2016), to a social sciences' analysis of the 3D printer's future trajectories (Urry, 2016).

By bringing the social aspect of emergence into a technical inquiry, the study develops an analysis which is based on emergent uses. This emphasis on usage rather than user, is to unpack relations between (social) agents and (technical) agencies. Emergent users, those that are 'barely within reach' (Devanuj & Joshi, 2013) are still relevant, but they only a part of my analysis. This analysis will be introduced later in this study through the concept of *emergent use groups*. Here, I analyse trajectories of AM through how different uses employ design techniques, prototyping strategies and perceive its users.

1.4.2 Product design expertise

The study is situated and approached from the perspective of product design. This perspective is one which inquires on the development of new and usable *products* through the practice of observation and conceptualisation. I will relate to products as the tangible artefacts and things which we interact with in our daily lives. Things that are technically, socially and aesthetically functional, and which can be found in our pockets, in our households, or in our urban environments. However, as online infrastructures and information systems become increasingly entwined in our daily activity, so is the need to perceive product design in relation to new forms of technological consumption. This is an emphasis which is very much embodied in Krippendorf's *The semantic turn* (2005), where he states that:

> While mass production became inscribed in the mass media of communication, fulfilling industry's dream of supplying universal markets with their goods and services, achieving nearly global coverage, products have become immaterial, informational, and entertaining. But as this is happening, heterarchical social forms, information networks, such as the Internet, are radically undermining traditional social hierarchies and the one-way communication of the mass media, encouraging a new kind of individual involvement in technology, enabling alternative conceptions of reality, and creating and reproducing diverse practices (p.3).

While product and industrial design practices place its roots to the shaping and rationalisation of mechanical products, the field of product design is emerging through generative, holistic and systemic design domains and sub-disciplines. Product design is seen to engage with both digital and physical products, and with services and systems (Clatworthy, 2013; Meroni & Sangiorgi, 2011); it is applied to enquiries into marketing and consumer behaviour (Luchs & Swan, 2011) and as managerial strategies through concepts such as *design thinking* (Brown, 2009; Cross, 2011; Dalsgaard, 2014).

While such concepts tie in with a market-driven version of product design, they all attach to core capabilities and characteristics that are said to be part of the practices of *designerly* expertise (Cross, 2006). This expertise encompasses the ability to navigate between diverse users and areas of use and with various sets of technology. In their field of practice, design experts combine tools, skills and methods to navigate a domain which ranges from surveying and observing stakeholders and conducting interviews to applying insights into new scenarios and testing them out.

The methods and tools that designers employ are often found within repetitive cycles of conceptualising, making and re-doing. These activities may be aided by the use of tangible mock-ups, prototypes (Pei et al., 2011) or probes (Mattelmäki, 2006). I emphasise this mode of inquiry as one that relates closely to a constructionist view of learning (Harel & Papert, 1991). This mode of embodied learning serves as a framework for which engagements with emergent technologies such as AM can be done in a cyclic, iterative fashion.

Whereas product design practice predominantly places attention on the front-end of design development, I propose a shift in focus towards a holistic application of design methods and tools. In other words, the study sees product design as a point of entry for which questions of technology and their uptake in everyday life can be addressed. Coming out of this holistic designerly emphasis, I build on existing topics of critical engagements in design and making (DiSalvo, 2014; Dunne & Raby, 2013; Ratto, 2011) through the introduction of theories of design critique.

1.4.3 Technological critique

Attention is then brought towards how a design practice can relate its activities to questioning technological development. I follow up with a discussion of AM, its status as emergent technology, and how it is being positioned within relevant literature. Through the lens of critical theory of technology (Feenberg & Callon, 2010), I provide a non-essentialist reflection on the various claims that are brought into AM. Critical theory of technology, which assesses technological development through the background assumptions of its relevant social users, provides a fruitful space for which to discuss matters of design in evaluating technology. I will connected my evaluation of technology with concepts from studies of technology, which include non-determinism (Feenberg & Callon, 2010; Winner, 2017), inscription (Akrich, 1992; Law, 1992) and (socio)materialisation (Leonardi, 2012; Suchman, 2007).

Within this critical view, design is seen as a process in which the capacities of technical artefacts are mediated by situated uses and which together provides the artefact with a purpose. Furthermore, I argue that a design-oriented perspective on technology has the capacity to de-contextualise purpose and provide new grounding to future technological visioning (Resch et al., 2018).

1.5 Research through Design (RtD) study

The study is a product design inquiry. It is motivated by the open-ended nature of qualitative inquiry (Denzin & Lincoln, 2018) for engaging with multiple methods and activities such as making, arranging and observing. It does so in order to construct a particular and subjective perspective on developments in AM technology.

Through the study's emphasis on practice-led research, it resembles a RtD study (Frayling, 1993; Koskinen et al., 2011; Stappers & Giaccardi, 2017), which puts emphasis on generating knowledge *through* acts of design. As a designer-researcher I am therefore embedded in a practice which is craft-oriented in its way of thinking through the hand (Sennett, 2008). This is exemplified in **Error! Reference source not found.** which shows a design

Figure 4 – Student designer assembling a plant terrarium consisting of 3D clay- and resin-printed materials. Photo: William Kempton.

student engaged in one of several workshop activities conducted. Here, a student designer is seen assembling a 3D printed terrarium.

The study is engaged with making artefacts as a way of informing and providing a situated view of social and technical contexts of AM. As is often seen with research projects emphasising such a designerly approach (Martinussen et al., 2014), the project engages with the making of artefacts and objects for speculation and discussion. This approach to product design brings to use its tools and methods for communicating and contributing to theoretical discourse. In taking on this approach, I seek to understand how product design tools might engage with how emerging technology is contextualised and understood. Through the facilitation of workshops with student designers and architects, the development of my own research practice and the observation of related practices, I have generated sets of research data which I have used to develop and build my arguments.

1.6 Summary of publications

The purpose of this exegesis is to collect and advance the arguments that have been built through research publications. In this section, I briefly summarise each publication its arguments. I then place each publication in relation to the other and explain the coherency between them and this exegesis.

1.6.1 Publication 1 – Design Issues and Orientations in Additive Manufacturing

The first publication (Killi et al., 2015) introduces a focus on product design by addressing the need to investigate the means and processes of AM trough a product design position, which involves key attention to the conceptual development of new processes for AM products. By unpacking development models on AM according to costs and co-productive value, the article presents a designerly categorisation on output areas of AM. These areas are defined through terms such as *representations, for manufacturing* and *as manufactured artefacts.* While these areas represent existing modes of use, it attempts to illustrate them through a series of designed prototypes, mockups and artefacts. In doing so it focuses on building a relation between design practice and AM.

The background for this emphasis is that while RP has dominated the design use and uptake of 3D printers through the making of detailed prototypes and mock-ups, attention needs to be focused to better orient AM in terms of holistic product design strategies. As such, a novel approach to designing for AM is introduced, which is titled AICE (Adapt, Integrate, Compensate and Elongate). This approach, which was developed in Killi's doctoral thesis (2013), can be understood as bridging the possibilities that lie in AM with an emphasis on product design. In all, this publication reflects on the increased attention towards the materialities, tools and production of AM, and argues that the dominant discourse should be oriented towards product design.

1.6.2 Publication 2 – A Design Sociotechnical Making of 3D Printing

The second publication (Kempton, 2017a) takes on a sociotechnical perspective of the development of AM technology, which emphasises an analysis of the situated uses of AM. In doing so it attempts to identify how distinct users contribute to shaping an understanding in relation of design. Through the book chapter I introduce a set of theories which come from studies of science and technology (STS), which subsequently places the emphasis on the social constructions of technological uptake. Drawing on relevant theories (Bijker, 1997) a series of *relevant social groups* are identified and discussed. These groups include laypeople, business management, 3D printer inventors and designers. I elaborate on current theories, key concepts and goals that each user group brings in its perception of what AM does, according to their own disciplinary positions. The argument forwarded is based on a social constructivist idea of technological development as one that is constructed through social intervention and situated use.

The theories introduced in the book chapter provides me with grounding to further my own approach to interpret how the interaction between different actors plays into the construction of technology, which I will characterise as adhering to a subjectivist epistemology.

1.6.3 Publication 3 – The Impact of Making

The third publication (Kempton, 2017b) hones in on design expertise and the material practices of AM. The publication initiates a discussion on the role of prototyping in design development, and provides an emphasis on its role as a filter to further refinement of abstracted design ideas. Following a brief review of the growing interest in 3D printing as AM, I discuss forms of prototyping through case-studies centred around three concrete product design projects. Using participant observation as principal method, I outline how digital fabrication changes the character of design development. Whereas the former notion of RP centres attention to concrete functional or aesthetic aspects of a product in development, AM implies renewed attention to digital information networks. This is seen through how management theories such as mass-customisation and agile software development principles from software engineering confront product design with new attitudes towards prototyping. Underlying the design cases, I introduce a novel prototyping strategy which takes into account the hybrid nature of AM. Named *releasetyping,* this new prototyping strategy can be seen as dynamic in its digital form, yet fixed as it is physically reproduced. This discussion brings closer attention to the purpose and diverse uses of artefacts within an AM-oriented product design development.

1.6.4 Publication 4 – Meeting Learning Challenges in Product Design Education with and through AM

The fourth publication (Kempton et al., 2017) takes on some of the issues related to AM and pedagogies of learning. Principally, this publication argues that if AM is to play a different role within design as mere material fabrication, focus must be shifted from technique to a broader contextualisation of emerging technology in societal contexts. In the publication, I start by posing a set of challenges relating to AM in product design and establishing how these challenges are incorporated into design education. Following a brief discussion of change, technology and the position of design as a social practice, I continue with a focus on the role of fabrication labs as a site of learning, which is then explained in relation to

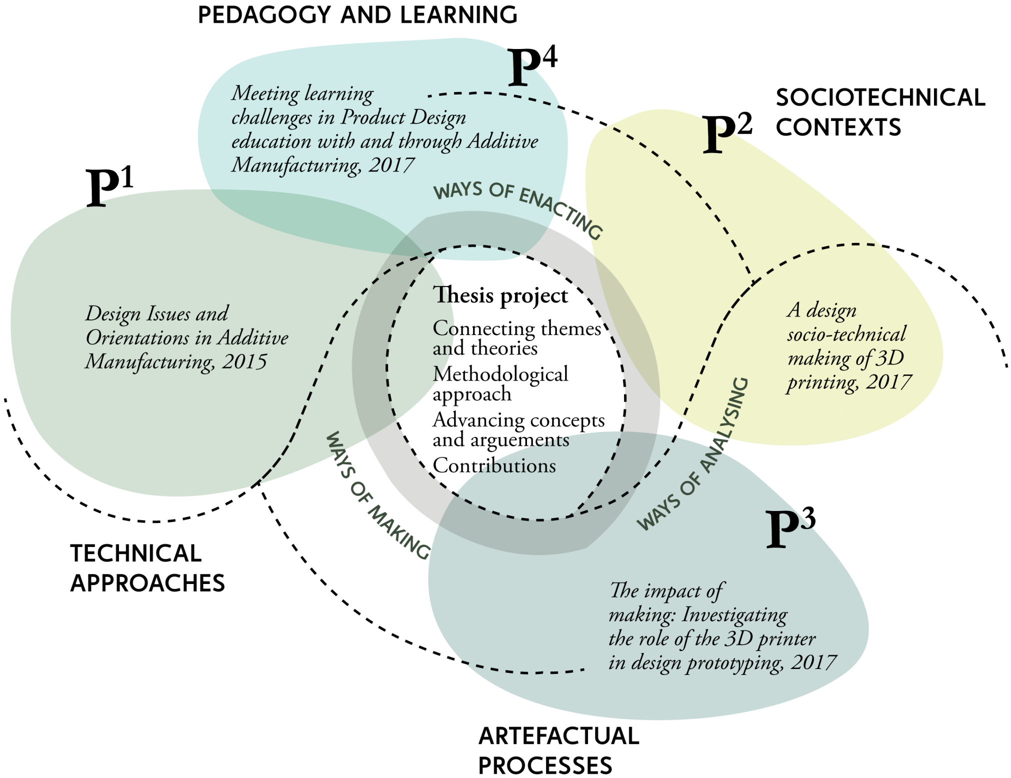

Figure 5 – Each publication takes up a distinct theme within the research area. The work of this exegesis is to connect these themes and theories for advancing the overall methodological view. Illustration: William Kempton.

the description of several making engagements conducted with students at The Oslo School of Architecture and Design (AHO). Through this qualitative practice-oriented inquiry, attention is brought to specialist skills training, critical study and interpretation of material, computational and socio-economic conditions and contexts that surround digital fabrication. What specifically comes out of this focus is a model, titled the Additive Experiential Learning Cycle (AELC), which oscillates between a formal, technically oriented version of design and one that is constructive and socially oriented.

1.6.5 Connecting the dots in the exegesis

The four publications take up different themes and points of analysis within the larger scope of the study, as Figure 5 illustrates. The first publication (P1) delves into concrete technical approaches to AM and argues that more attention needs to be brought to developmental strategies of use by product design. As opposed to the first publication's emphasis on product development, the second publication (P2) takes on a different set of theories to discuss the social entities that make up the development of AM technology.

In the third publication (P3) emphasis is oriented back towards the processes of artefacting in design development. I conduct observations of expert designers and analyse new product development (NPD) processes to reveal new opportunities for design in AM. The publication directs the discussion towards digital design strategies, and calls for renewed attention towards the hybrid, digital/analogue nature of AM tools.

Whereas the first three publications (P1-3) are primarily interested in the socio-technical adoption of AM, the fourth publication (P4) brings attention to learning challenges related to the product design uptake of AM technology. As a key argument of the study is that AM needs to be understood better within situated practice, the publication builds on experiential learning as a form of situated learning.

As Figure 5 illustrates, the exegesis aims to connect the seemingly diverse areas that are taken up in each publication into a single coherent structure. This connection is made through introducing new concepts for design-centred approaches and analytical frames. Key concepts include *design-making critique, emergent use groups* and *technological design frame,* which provides a framework of situated, technological analysis. The title of this exegesis, *Unpacking Making: A Product Design Critique on the Emergent uses of Additive Manufacturing*, is chosen to emphasise how sociotechnical change can be critiqued from the perspective of product design.

Seen in relation to each other, the publications contribute to frame my overall methodological view. Relevant theories and arguments which are advanced in each of these publications are discussed further within this exegesis.

1.7 Form of exegesis

The study examines how design practice uses *making* as a form of knowledge research, and in doing so does a qualitative interpretation of AM use. Framed as an RtD inquiry, I have conducted a series of individual design projects, which guided the development of this thesis in tandem with a critical study of interdisciplinary and emergent research literature (Bertling & Rommel, 2016; Greenfield, 2017; Resch et al., 2018). These projects, which facilitated student-led exploration and individual work, are described in relation to a constructionist, experiential learning model. I do this as the practice-based research is in part conducted in the context of master's level design studies.

Equipped with this theoretical framing, I provide a critique of AM through a critical theory of technology and I assess the background assumptions that are contained within relevant literature. Through this assessment, I locate perspectives where technology is seen as guiding and determining its own outcome. These trajectories might lead to optimistic and dystopic visions of AM. I argue that such views in effect give little agency to design inquiry. Rather, through a non-deterministic position, in which social and technical agency is taken into account, I relate the discussion of emergence to that of design practice and production, casting this also in a wider frame of digital fabrication.

Through this discussion, I extend an experiential learning model which links aspects of making, analysis and critique. This model of knowledge-making is introduced through the concept of *design-making critique*, as an approach to a sociotechnological inquiry into the emergent uses of AM. This concept is argued as method for generating data that is sampled through design in the same way as a sociologist might sample his research subjects through stratified or systematic sampling methods. Attached to this approach is also an analytical frame, which is introduced as the *technological design frame.* This analytical frame draws on relevant STS theories which serves as an outline against which to assess and evaluate emergent uses of AM technology.

Having investigated relevant theories and concepts to facilitate an assessment of designerly inquiry into AM technologies, I will discuss the potential future uses and uptake of AM technology. Here I make connections between existing technological fabrication phenomena and the anticipation of future interests for the field.

1.8 **Thesis outline**

This introductory chapter provided a brief summary of the study, introduced a set of research questions that guide this research and outlined a set of themes that the exegesis takes up in later chapters. Through a brief reframing of AM technology, I call to attention its cultural, political as well as technical aspects, and argue that it could be interpreted more holistically through a product design framing. In the chapter I also provide as summary of the research publications that are attached to this study was provided, followed by a description of how they relate to this text.

In the second chapter I discuss key related framings. The chapter begins with a review of product design practice as a form of technological inquiry, which is guided by, but not restricted to a market-driven practice. The chapter then provides a brief overview of current developmental strategies, and moves them into a space of critical inquiry. By introducing key framings such as critical making (Ratto, 2011), I briefly discuss how design has the capacity to interpret and investigate everyday phenomena through acts of making. A review of critical theories of technology is presented, providing me with relevant theories to engage with a critique of AM. Last, I recount how the project develops around a reflective practice.

In the third chapter I present the research methodology. I frame the research study as one which follows a constructionist paradigm and developed through a qualitative RtD framing. This is briefly explained as a form of inquiry which orients generative design activity towards the making of new knowledge. Specifically, I explain how such a practice-led activity is informed by design techniques, design tools and research methods, which span actions such as *making, observing* and *arranging.* These actions are then explored through a series of qualitative research data. This data includes a series of curated exhibits, digitally fabricated artefacts, participant observations, and interviews.

Following the descriptions of methods, tools and techniques, the fourth chapter hones in on a discussion of craft and inquiry into AM. In this chapter, I question the pathways and conceptual thinking that goes into making *with* and *through* AM, calling into attention constructionist and experiential frameworks for learning. Subsequently, I discuss how a critical making inquiry may be better understood in a product design context by bringing attention back to prototyping as facilitating an experiential learning which provides knowledge on AM. The concept I introduce called *design-making critique* starts with a critique of the methods and tools used within a design project, and moves on to critique the designers' role in the development of new technology.

The fifth chapter applies a critique of AM. Building on earlier introduced concepts for critiquing technology, I introduce concepts for describing and analysing design exploration within a larger socio-technological grid. These include *emergent use groups* and a *technological design frame*, which are discussed in accordance with the 3D gingerbread project to discuss the incorporation of AM into discreet, subjective uses.

I then deliberate possible AM futures by drawing on related phenomena of material fabrication. Furthermore, I discuss the pedagogical implications my research might have on designing for AM, as well as pointing to issues regarding future research on AM.

Finally, the concluding chapter closes the study and provides a summary of the new knowledge obtained through the argument that the study presents and the contributions it provides.

2 Positioning fields, theories and design practices

The previous chapter gave a brief overview of the study and described the study's objective to provide a critique of AM through product design knowledge and expertise. Guided through the principal part of my research question, the chapter aimed to establish the emergent uses of AM. To do so, I initiated a critique of claims and discussions related to AM. Through a brief historical context of its development and use, I arrived at a contention that AM must be seen as more than a means of material manufacturing. I summarised the views of related terms, such as *rapid prototyping* (RP) and *3D printing,* making it apparent that AM serves a purpose beyond a dominant, manufacturing paradigm.

In this chapter I review and position the thesis to key related framings, which include product design practices, critical making, critical theories and technology, critiques of AM and reflective practice. These framings allow me to orient product design towards inquiring on AM technology. This inquiry also steps towards critiquing visions and rhetoric that is carried through by relevant literature on design, digital fabrication and AM. I also consider the second part of the research question, which is oriented towards the practice concerned with providing a situated contextualisation of the technology in question: *How can AM be unpacked through design expertise and analysis*?

Following this review chapter, I explain my selection and use of research methods, design techniques and tools, which informs my practice-led methodology.

2.1 Positioning product design

To advance a view on the critical material engagement *through* product design practice, I first discuss some of the shifts that need to be made in

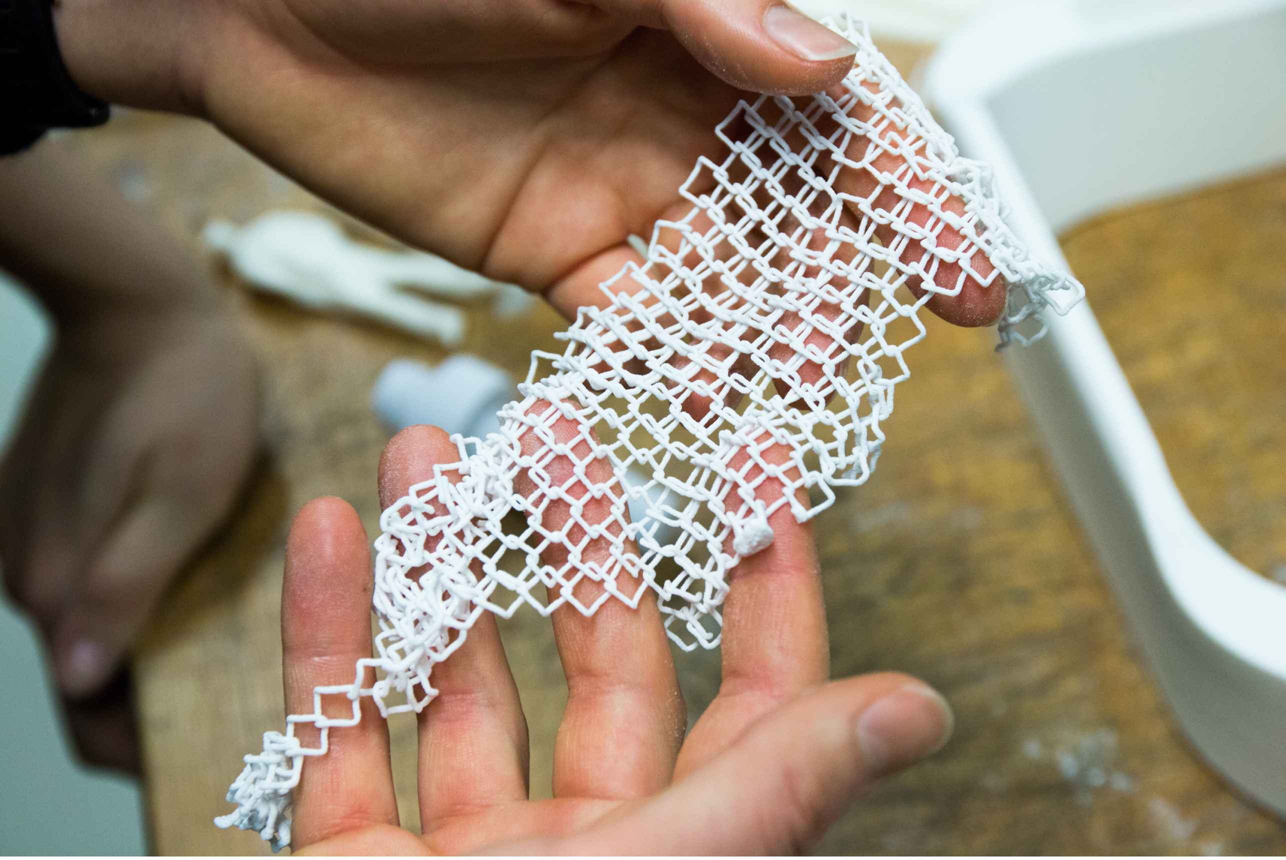

Figure 6 – A sample of a nylon mesh, fabricated on an SLS 3D printer. While the material itself is rigid, the way in which it constructed, by interlocking individual parts, makes it appear soft and pliable. Photo: William Kempton.

order to situate design practice within the crafting of mental models for digital fabrication. I start by repositioning product design from a market-driven practice to an anticipative and investigative practice. The objective for this reframing is to advance the capabilities of product design to engage with new potentials and problematics related to the uptake and emergence of AM technology. Figure 6 illustrates now potentials, such as the interlocking of rigid nylon parts may give it a soft and pliable feel.

Through this reframing, I explicitly emphasise the critical and productive activities which are involved in designing as a way of developing reflections around AM technology.

2.1.1 Product design and the market

In a pre-industrialised context, artefacts and goods are conceptualised and crafted under that same roof by skilled craftsmen (Sennett, 2008). Today, the production of consumer goods is predominantly a professional activity involving several skilful and specialised activities. With the advent of industrialisation, the production of goods is dispersed in different places and locations, through access to labour and the successful harnessing of power. Labour is divided among those who conceptualise new designs, those engaged in the manufacture of goods, and those involved in its distribution and sale. As a result, the industrialised process of designing a product becomes a strategic activity which requires a diverse set of specialised skills and expertise. In managerial literature, this process is commonly referred to as the New Product Development (NPD) process.

The NPD process can be understood as an action which transforms market opportunities into new products (Krishnan & Ulrich, 2001). This process generally involves a diverse series of actors, some that uncover market opportunities, some that conceptualise and envision its appearance and use, and others that are responsible for releasing the product to a market. To cope with the increased demand to develop products within time and cost, considerable advances have been made in managerial strategies for NPD (Takeuchi & Nonaka, 1986). Just as products increasingly flow between digital and physical space, so have these strategies been adopted to account for increasingly rapid and incremental product launches.

Existing literature on NPD emphasises *design* in different ways. One version confines design to the front-end of the process, where the transformation of *fuzzy* ideas into concrete concepts and prototypes is emphasised as a core design activity (Koen et al., 2001). In such versions prototypes resemble filters and representations for abstract design ideas. The act of prototyping is therefore understood as an action between creating and refining to-be artefacts through prototypes (Lim et al., 2008). Other strategic versions of design see it as a holistic activity. Strategies such as design-driven innovation (Verganti, 2009) offer a situated view on innovation by relating design to cultural value. Central to this strategy is the argument that the success of a new product or service is the purposeful development of new *meaning*. In other words, people use things that have profound emotional, psychological and sociocultural value in addition to its utilitarian needs. This concept is forwarded as an alternative to technically oriented strategies that are highly present in innovation research. Rather than as a bolt-on to other managerial strategies, a holistic view on design provides an important backdrop to this thesis' reframing of product design.

Because of its strong affiliation with market practice, product design is broadly concerned with building strategies and methods for conducting design work. Strategies such as Kees Dorst's *Frame Innovation* (2015) propose a ground-up *design thinking* methodology as an approach to problem solving. Dorst's (2015) argument is that traditional problem-solving is a general human ability and not reserved for designers. His concept of *frame creation* is introduced as a starting point from which to deal with the complex, networked world that surrounds us (Dorst, 2015). Rather than being a linear, instructive approach, the concept of frame creation involves a series of steps which sorts out different kinds of activities into coherent units of framings (Dorst, 2015, p. 99).

Dorst's (2015) concept of *frame creation* resonates with an increasing amount of literature centring on design and the complexity of everyday life. Literature, such as Donald Norman's (2010) *Living with Complexity* discusses complexity as an unavoidable necessity in both nature and modern societies. Just as the cockpit of an airliner might seem entirely confusing to the onlooker, to an airline pilot, it contains the necessary instruments for safe navigation. Where Norman (2010) places his critique is on the unnecessary confusion of even simple designs, such as an array of unidentified light switches.

The topic of complexity leads me to examine design and its role in shaping technologies, specifically the ways in which design can be repositioned to navigate between seemingly linear advances in technology and the complexity of societal uptake. To address this issue, I discuss design as a critical and future-driven practice.

2.1.2 From a market- to a future-driven practice

Design continues to take up an increasing amount of attention in the innovation strategies of large global enterprises (Deserti & Rizzo, 2013). I direct attention towards a version of design that is dislocated from the contemporary needs and desires of the marketplace, to that of an anticipatory role. As such, my reframing of design aligns more closely with the concept of *advanced design* as a mode of anticipating on emerging needs and desires (Celaschi & Celi, 2015). The term, which is linked to the advanced, front-end of design-driven innovation, understands the designer as a manufacturer of possible futures, rather than adhering to the *feasibility* and *producibility* of the marketplace. The logic of this reframing, from a market- to a future-driven practice, is to offer an alternative vision where ethical and environmental implications are addressed. These implications might include mass-commodification and over-consumption.

Two concerns come out of this reframing. The first relates to how design is conceptualised in these advanced futures. The second relates to the methodological concerns these conceptualisations of design might have.

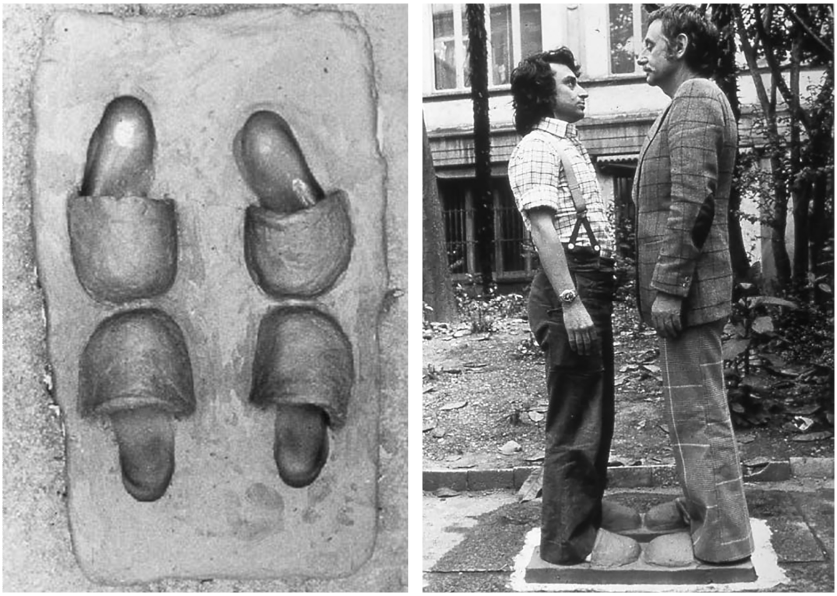

Figure 7 – Ettore Sottsass and Franco Raggi in a pair of constraining shoes for stable and obligatory frontal juxtaposition, Milan, 1975. Photo: Archive Casabella.

2.1.3 Design as a critical practice

As an alternative to being a market-driven practice, design is also capable of critique and speculation. These critiques may take place within everyday phenomena, such as the way in which our society adopts new technical innovations, as well as changing political climates. Early critiques are found in Rayner Banham's (1980) anticipation of the second machine-age of the post-war period. This is a period in which the mass-domestication of electronic goods such as kitchen aids and tape recorders also contributed to new forms of mass-communication and entertainment.

What is understood from the dominating direction of design criticisms in Western countries in the post-war period was the need to inform the public about the machinations of commerce and to educate them to make, buy and sell better products (Twemlow, 2017). At the same time, industrial design became painfully aware of its own machinations, as is epitomised by Victor Papanek (1972) in his seminal book *Design for the Real World*. Here, Papanek (1972) argues for new directions of design which detach from what he saw as the homogeneous, modernistic agenda of contemporary design and architecture education.

In particular, the ability of design to enact on its critique is a methodological move of particular interest to my framing of product design. Such early forms of design critique are found in the Italian 'radical' design movements, which sprung out of the developing socio-economic downturns of the late 1960s and early 1970s Italy. Groups such as Global Tools, Archizoom and Superstudio, involving characters such as Ettore Sottsass, Andrea Branzi and Alessandro Mendini, predominantly focused their critique on urban development turning on itself. In projects such as the 'No-stop City' (Branzi, 2006), Andrea Branzi and Archizoom sought to provide commentary through their architectural practices on what they considered important issues. Concepts which tackled the historical functions of a city as in conflict with the introduction of heavy industry. Through architectural critique, they envisioned a 'city freed of architecture, where technology and nature were not harmonized, but merged together' (p. 152).

Along this vein, experimental projects such as Global Tools sought to problematise emerging phenomena of the time, such as the increased use of plastics and electronics, through a series of practical workshops. The Global Tools project, which lived between 1973 and 1975, was organised around several sub-topics including the 'Body', 'Construction', 'Survival' and 'Theory'. Intentionally regarded as 'non-pedagogical' and 'multi-disciplinary', these workshops produced work which intentionally broke with the idea of positivistic and rationalistic 'science' of design. Rather, it sought to 'zero out' the pre-existing link between design, art and commerce. Figure 7 shows a workshop project which challenges the idea of a comfortable, dynamic design. The shoes, titled Scarpe Vincolanti, force their users into a 'stable and obligatory frontal juxtaposition' (Borgonuovo & Franceschini, 2015, p. 55). It also recalls a need to return to physical, verbal discussion.

The early nineties opened for yet new forms of criticism, through physical design activities, open-sourcing and online engagements. Labelled as *Critical Design*, designers such as Dunne and Raby (1999; 2013) and James Auger (2013) sought to problematise concepts of optimisation and rationality in the design of everyday electronic devices. Through fictional 'placebo objects', design works and artefacts could be understood as a form of visceral criticism.

The production of critical design artefacts, such as those of Dunne and Raby (1999) succeeded in reflecting on the relationship between product design, consumer electronics and new aesthetics of use. While Banham (1980) envisioned a Second Machine Age in which machines complemented physical labour, Dunne (1999) brought in a critique of the envisioned Third

Machine Age, in which silicone chips and computational software complemented social activity.

2.2 Critical making

2.2.1 Design as a critical making practice

While critical design provides product design imaginaries, my reframing of product design is more concerned with providing recipes for how critique on technological development and social uptake can be introduced through product design's developmental practices. To advance this idea, I use the concept of *critical making.* The term which is introduced by Matt Ratto (2011), comes out of informatics studies and embodies a capacity that is relevant for my orientation of product design.

Critical making is explained as an activity for understanding and developing abstract concepts and theories through making. Specifically, the act of making artefacts is advanced as a central activity for developing abstract theory. Rather than emphasising the artefactual outcome of the making activity, Ratto (2011) stresses that critical making is to 'extend knowledge and skills in relevant technical areas' (p. 253).

As with other approaches to materialising knowledge through making, critical making specifies physical, constructive material work as a key ingredient. However, Ratto (2011) makes explicit connections for critical making to the analysis of scholarly literature. His focus is not to create an 'evocative object' or a thing that brings certain feelings or images to mind. Rather, he contends that

> the final prototypes are not intended to be displayed and to speak for themselves. Instead, prototypes are considered a means to an end. Their purpose is to achieve value though the act of shared construction, joint conversation, and reflection (Ratto, 2011, p. 253).

Figure 8 illustrates one of such critical making activities, where Ratto uses the shared practices of making as a method of facilitating critical discussions on the subject of distance education. Specifically, a discussion is oriented towards the criticism of distance education lacking the 'sociality of face-to-face interactions' (p.255). The artefact shown is one of several created during short event, hosted at the Royal College of Art and at the Imperial College, which involved students making small 'bristlebots' (small robots that move with the help of a toothbrush and motor). While Ratto himself acknowledges the gap between the objects made and the topic under

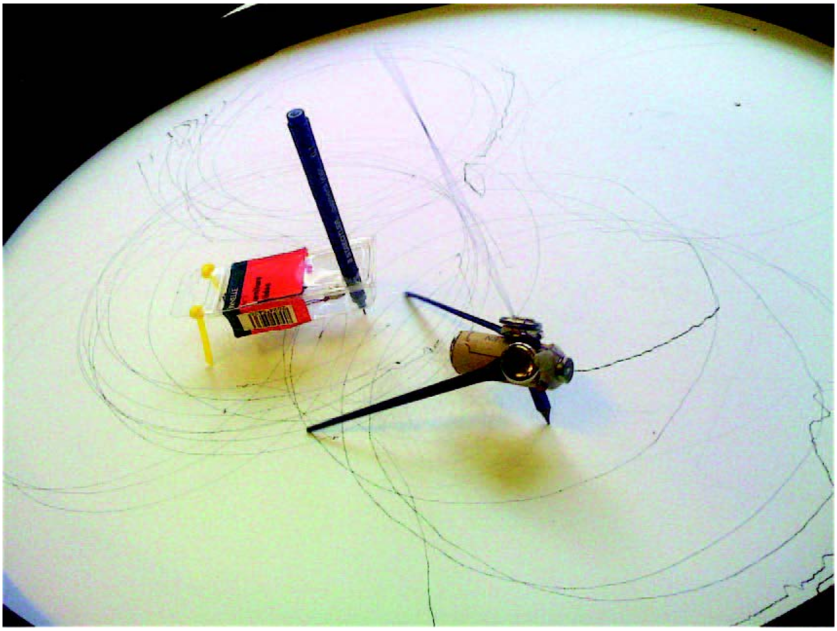

Figure 8 – The Drawbot, an artefact created through a critical making workshop hosted by Matt Ratto at RCA and Imperial College, to facilitate critical reflections on long distance education. Photo: Ed Burton (Ratto, 2011).

discussion, it addresses the need of relating making activities with the development of theory, which in his case was on distance learning and physical interaction.

The term critical making borrows from the popular uptake of *making* and *DIY* (Do-It-Yourself) interest. While DIY repair and mending is still a necessary activity in less affluent societies (Atkinson, 2006), the phenomenon has seen a strong surge in recent decades in economically affluent societies as a reaction to consumerism. The maker movement, as an embodiment of these phenomena, can be likened to a form of material activism whose participants voice their expressions through material tinkering. The maker movement (Dougherty, 2012) is associated with activities such as Maker Faires that are arranged around the globe. Makerspaces, Fablabs, hackerspaces and a plethora of online sharing forums (thingiverse.com, instructables.com, youmagine.com), have come to represent some of the venues in which maker subcultures are being cultivated.

A variety of literature suggests that these venues place considerable emphasis on emerging technologies, particularly those relating to material production (Gershenfeld, 2008; Walter-Herrmann & Büching, 2014). The literature on personal fabrication (Mota, 2011) advocates that as distinctions between virtuality and materiality fade away, approaches to personalised material production will become more feasible. The role of personal fabrication laboratories such as FabLabs is then envisioned as important in the development of social networks (Troxler, 2014). These arguments may however be put under scrutiny because they are laden with technological optimism and they follow a belief that digital fabrication technologies will inevitably become as efficient as contemporary production methods. While such belief systems are often evident among advocates of hacktivism (Söderberg, 2013), they are in need of scrutiny by reflective approaches such as critical making.

While Ratto's version of critical making aligns more closely with understanding concepts such as legislation (specifically the potentials and consequences of open-sourced sharing) and citizen involvement (Ratto & Ree, 2012), Hertz's (2012a) version of critical making aligns more closely to how artefacts themselves might embody critical reflection, in addition to being process driven. Hertz's (2012a) self-published book *Making Critical Making* is born out of a reaction to the perceived sanitation of the term *making*, as something fixated on desktop 3D printing, DIY kits and short term gadget projects. As Hertz (2012b) proposes, critical making allows 'the builders of technology – whether hackers, engineers, industrial designers, or technology-oriented artists – to step back and re-evaluate the assumptions and values being embedded into their technological designs' (2012b, para 6).

In relation to the core topic of this study, namely forwarding a critique of AM through a product design practice, critical making is a valuable framework for the development of my own attempts at engaging with abstract concepts through the making of material artefacts. As pointed out in prior research, AM draws a considerable amount of interest beyond the technical confines of its process. Its many latent social capacities, from new conceptions of labour (Ratto & Ree, 2012) to lay-person involvement (Hermans, 2015), become topics of interest for product design, which a practice-led research is suited to explore.

2.3 Critical theories of technology

In this section, I shift focus to the phenomenon of technological development. I will talk specifically about theories on technological change and the ways in which this change is encountered by and shaped through human engagement. The theories I discuss come out of the multi-disciplinary field of STS, which is broadly interested in how society, culture and politics play a part in technological innovation. Following a brief summary of the theories of sociotechnical change, this section discusses the link between the features that are said to be intrinsic to a technology, and the ways in which we can interpret them through design. Through the review I will hone in on three relevant aspects: (a) *technological non-determinism* as an alternative to a traditional view of the autonomy of technology, (b) *inscription* as a concept for addressing relationships between the design of technological objects and their anticipated features and (c) *materialisation* as the facilitative process in which technology continuously emerges.

Before providing a review and giving a fuller description of relevant theories and concepts, I first explain briefly what is brought into the term technology. *Technology* is informally associated with devices, things, techniques and other man-made objects which are both digital and physical in form (i.e. smartphones, digital cameras, internet search engines, Bluetooth connectivity and CAD software). While these objects are undoubtedly relevant aspects of technology, they arguably operate within a larger sphere of a technological practice. For instance, many smartphone camera apps use particular sounds when capturing photos which are reminiscent of a mechanical shutter being drawn open. While there is no such mechanic movement in the smartphone camera, it is culturally recognised as the point at which a photo is taken. Similarly, popular CAD tools incorporate features for raising patterns onto surfaces often labelled *emboss*, in reference to the traditional process of embossing seals and emblems onto official documents.

By looking closely at these features and asking questions about how they came to be, we can trace their relations to societal circumstances. And by the same logic, we can even draw visions about how they could be constructed differently. In this sense, I regard technology as the technical, cultural and organisational aspects of technological practice (Pacey, 2004). Viewed in this way, technology governs the economic and industrial activities with which we engage, as well as the ethics and values by which we live. In short, our relation to technology is so tightly bound that it can be abstractly understood as *forms of life*, as Langdon Winner (1983) eloquently puts it.

Winner (1983), who draws attention to a philosophical view on technology, argues that technical things are all too often seen as 'too obvious to merit serious reflection' (p. 250). Rather, Winner (1983) suggests that seeing technology as a 'form of life' allows us to focus our attention on evaluating how technological innovation might influence life, as our existence would be unthinkable without them.

2.3.1 Constructivist theories of technology

To evaluate technological innovation further, I turn towards relevant theories of technological development that are found within the field of STS. Seeing a surge of interest in the 1980s, these sociotechnical theories can be seen in response to contemporary government and industry policies which emphasised linear models of innovation (Williams & Edge, 1996). Specifically, the field rose to challenge perspectives which promoted technological development as 'neutral' and 'inevitable'. Relevant theories to question these assumptions include the Social Construction of Technology (SCOT; Bijker, 1997; MacKenzie & Wajcman, 1985; Oudshoorn & Pinch, 2003), Actor Network Theory (Latour, 2005; Law, 1992) and Social Shaping of Technology (Williams & Edge, 1996).

A central argument of SCOT advocates lies in providing a social emphasis to accounts of technological development. This emphasis on social actors presents as a counter to the apparent determinism of technological systems. Such an account is found in Bijker's (1997) famous analysis of the development of the bicycle at the turn of the 19th century. Here, he develops a framework for building a clustered, multi-linear perspective to the historical development of the bicycle. Through what he describes as an academic detour, Bijker (1997) analyses how different users (*relevant social groups*) adopted their own interpretations of how different bicycle designs were perceived *(interpretative flexibility)*; while non-users considered the large-wheeled velocipede unsafe, its users saw it as a part of the risky nature of cycling. Only after the introduction of particular technologies, such as Dunlop's (1888) vibration-dampening rubber bicycle tires, did the double-triangle safety bike come to be synonymous with what a bicycle is today. This convergence is described through the concept of *closure/stabilisation,* which allows Bijker (1997) to review technological change.

To advance my own theoretical framework for this study, it is relevant to ask which concepts of SCOT are relevant, and determine how may they reveal social aspects of emerging technologies such as AM.

The advances made by SCOT offer a conceptual framework in which to interpret empirical data. Rather than offering new findings into the development of particular technologies such as the bicycle, SCOT seeks to contribute with a theoretical framework for understanding the social nodes which are at work in the development of a given technology (Bijker et al., 2002). As such, a significant emphasis of the SCOT framework lies in tracing (relevant) non-users and bringing them into the analysis of technological development. This is arguably an important move because it gives agency to those users that are not typically understood as primary research subjects.

This move has been particularly effective for my analysis and theory development, and I brought it into use in publication 2 (Kempton, 2017a) to develop a sociotechnical perspective of 3D printing. My selection of relevant social groups spanned from business managers and 3D printer inventors, to designers and laypeople. These user groups were selected to highlight key problems these users perceived in their assessment of AM. While my analysis attempted to touch upon the envisioned claims which were made of AM (e.g. Business management visions of a shift from ‘economies-of-scale’ to ‘economies-of-one’), the theoretical framework used was grounded in a contemporary view on AM/3D printing. However, there are challenges picking user groups which are deemed relevant for the particular analysis. It arguably does little for understanding the emerging characteristics and potential stakeholders of the technology in question. While this may be a criticism of the SCOT framework, it urged me to interpret technological development from a several social levels. This includes a micro-level view in which social agency is strong, and a macro-level where technical agency seems in charge. Questions are then oriented on how opposing perceptions of use and technological uptake can be made evident.

2.3.2 Technological non/-determinism

Central to discourses of technology development and organisation is the notion of *determinism*, which relates to the idea of cause, rationality and predictability. Technological determinism can be broadly seen as the overarching positioning of two distinct ontologies: (a) technology is neutral and linear and inevitably dictates the development of our society and (b) technical development is a continuous process of social, cultural and political interplay (Leonardi, 2009; Winner, 1983).

In Ellul’s (1980) version of sociotechnical development, technology is likened to a form of Darwinistic natural selection, where ‘among the countless factors operating within a society, one factor [political, scientific etc.], at a given moment, appears more decisive than the rest' (p. 67). While Ellul's (1980) determinism can be understood as a call to action (Misa, 1988), the fact remains that such deterministic opinions on technology are commonplace in everyday media. Seen from a cultural perspective, Slack and Wise (2015) discuss how technological determinism often organises the way people understand and act in the relationship between technology and culture. Their actions are often reflected in popular discourse, through commentary such as 'Google is making us stupid' or 'television is causing violence' (Slack & Wise, 2015, p. 53). From a critical perspective, Winner (1988) understands technological determinism to be the 'the idea that technology develops as the sole result of an internal dynamic and then, unmediated by any other influence, moulds society to fit its patterns' (p. 21).

Other versions of determinism are those which see culture as a major influence, or cause, of technological development. Such a *cultural* deterministic position bears much resemblance to the previously mentioned, technological deterministic position. However, it assumes that the social circumstances and the way machines and technologies are interpreted by stakeholders give them stronger intentions than the machine. By this logic, the shift from print culture to TV and radio can be seen as creating a 'tribal' media culture. Whereas the former produced rational and individualist subjects through its linear form, the introduction of the latter constructed more fragmentary and aestheticised subjects through the spectacles of film (McLuhan, 1994).

On a material, user level, it is also relevant to talk about determinism as a belief that it is possible to design *intent* into a product. Ihde (2008) addresses this topic in his discussion of *designer fallacy* as a concept in which designers can control purpose and intent within a technology through design. In Ihde's (2008) deliberation *against* this determined belief, he introduces a series of examples in which the designers' intent ultimately produces new purposes. Examples include the early typewriter, which was meant as a prosthetic technology for helping blind people to write, and Alexander Bell's intention to make a sound amplification device for his hard-of-hearing mother. What comes out of his discussion is a need to recognise that situations of use are considerably less transparent than they are often made out to be.

Last, a *non-deterministic* position offers a view which examines essentialist claims to technological and cultural cause and effect. This requires a form of analysis that is informed by seeing social influences on a micro-level, as well as the technical influences on a macro-level. A version of this is found in Misa's (1988) review of the argument of determinism in which he argues for such a two-sided analysis.

A more comprehensive argument for a non-deterministic position is found within Andrew Feenberg's (2010) Critical Theory of Technology, which similarly springs out of the constructivist framework. Feenberg (2010) talks about technologies as mediated through cultural heritage and tradition, and its adoption of 'neutral' technological devices as 'interaction between reason and experience'. Attached to his critical theory of technology is his theory of *instrumentalisation*. In it, he argues that while technological devices can be seen as having an inherent (instrumental) rationality, its applied and situated uses become interpreted, or instrumentalised, as they are placed in a lifeworld (Feenberg, 2010). This action, he contends, has a decisive influence on its design (Feenberg, 2010). The framework which is attached to instrumentalisation theory consists of an analysis of technology which occurs on two levels. First, the various qualities of a technology are decontextualised from its users, situations and things into basic technological parts and elements. Second, these *technical elements* are re-contextualised within technical, natural and social environments, which are essential for understanding the real-life context of technology (Feng & Feenberg, 2008).

2.3.3 Inscription

Building on Feenberg's (2010) critical theory of technology, I turn towards the concept of *inscription,* which is located within Actor-Network Theory (ANT) and closely linked to the concept of *translation* (Law, 1992). Whereas the social constructivist approach can be seen as an attempt to frame ways in which to create *social* ties with technology in development, ANT emphasises the relationships between different *actors (*human and non-human entities) and the way they are constituted through the specific roles they play. Rather than following the social actors as if to render the *social* stable and accounting for the shape of technological change (Latour, 2005, p. 10), ANT follows its analysis through as if 'things, quasi-objects, and attachments are the real center of the social world' (Latour, 2005, p. 238). In order then to see relations between its actants (human and non-human) and to understand the way in which objects can be said to have certain 'determinable' characteristics, ANT employs the concept of *inscription* (Akrich, 1992). The concept accounts for how technical objects are *inscribed,* meaning that they translate interests into material form. In considering the process of translating these interests, Akrich (1992) draws attention to design by saying,

> Designers thus define actors with specific tastes, competences, motives, aspirations, political prejudices, and the rest, and they assume that morality, technology, science, and economy will evolve in particular ways. A large part of the work of innovators is that of 'inscribing' this vision of (or prediction about) the world in the technical content of the new object. I will call the end product of this work a 'script' or a 'scenario'. (p. 208)

For instance, a designer may inscribe certain characteristics to a product or service in anticipation of it performing a certain action. These inscribed anticipations could be seen to determine the particular use of the object, while also calling into question the perceived flexibility of the product. Seen this way, inscriptions can be either strong or weak, according to how tightly bound a designers' conception of an object's characteristics are in relation to its emerging function (which consequently relates to other networks of inscriptions).

Hanseth and Monteiro (1998) stress that inscriptions are not deterministic in the sense that specific actions are 'hard-wired' into artefacts. Rather, they are seen as a balance between the objective uses of artefacts on the one hand, and the subjective interpretation and perception of flexibility on the other. To draw the concept of inscription into analysis, Hanseth and Monteiro (1998) introduce a set of points of analysis: (a) how anticipations of use are created by designers, (b) how this is translated into materials, (c) who is engaged with inscribing and (d) what is the strength of the inscription.

These points of analysis are also relevant for the development of my own analytical framework, as it brings attention to design intent and outcome. Reformulated as a set of questions, Hanseth and Monteiro's (1998) analysis of inscriptions could ask the following of a design: What is the anticipated scenario, and how are these anticipations translated into products and services? Who is engaged in the process, and are the inscriptions strong or weak?

The objective of this section is not to build a comprehensive review of the entire field of ANT. Rather, it is to locate specific concepts that allow me to approach the emerging field of AM. I use the concept of inscription because it allows me to interpret technological systems, such as AM, as continuously emergent phenomena. It does so by assuming that the uses of AM are bound by a network of CAD tools, data formats, design experts, laypeople, feedstock materials and 3D printing tools. All these actors inhibit affordances which may translate into new inscriptions. As actors are joined together in novel ways, such as those made by the layperson enthusiasts' uptake of desktop fabrication, it inscribes yet other visions to the AM technological system.

The discussion then needs to be oriented towards the concept of *agency,* and how it relates to the inscription of new socio/technical/material characteristics. I will draw on recent developments in *sociomateriality* which can be considered a sub-genre of ANT, and which is emerging in fields such as organisations management and information systems.

2.3.4 Materialisation

While the constructivist approach is to consider inscription as forms of *agency* which are inscribed *onto* objects (rather than producing them), critiques can be made of the emphasis that agency is seen as a commodity in itself (Barad, 2003). Specifically, the idea that agency is somehow subjected to human intentionality is a core issue that is brought up in recent literature examining *sociomateriality.* Influenced by the writings of Barad (2003), Suchman (2007) and Orlikowski and Scott (2008), sociomateriality emerges as a genre of research coming out of organisational and management studies. Departing from previous generations of (social) constructivist theory and its emphasis on people's interpretations of technology, sociomateriality can be seen as increasingly focusing on the day-to-day interactions with technologies in use, and the inherent inseparability between the technical and the social. As such, it draws from Barad's (2003) position as agential realist, in that *social* and material agencies can be seen as mutually dependent. More specifically, it contends that the notion of sociomateriality can more precisely be explained as the 'enactment of a particular set of activities that meld materiality with institutions, norms, discourses, and all other phenomena we typically define as "social"' (Leonardi, 2012, p. 24).

While social-constructivist frameworks such as SCOT have concepts such as closure/stabilisation to describe the point at which different relevant users settle around a given technology, sociomaterialists use the concept of *sociomaterial assemblages* to describe the temporal stabilisation of social and technological agencies, particularly in the context of the workplace (Suchman, 2007).

In the making of my own conceptual framework, sociomateriality draws particular emphasis to the point at which social phenomena and inherent material characteristics are melded and entangled together. In this sense, *materiality* emphasises that technologies have certain material characteristics and properties which are enduring, which allows users to engage with them. Recognising (sociomaterial) practice as the playing field for human and material agencies, as well as their characteristics, allows me to focus in on the process at which they are negotiated. This process is necessarily emergent because it is continuously subjected to social power relations.

2.4 Critiques of AM

In this section, I examine some of the opposing claims and discussions that are tied to AM. Arguably more than a process for manufacturing goods, AM is now a field of interest spanning several disciplinary fields and practices. Whereas previous conceptions of AM were oriented towards product development (Evans, 2002), I show here how AM is taking part in discourses outside of engineering and design to include political and cultural agendas. As a part of this analysis, I review both the optimistic and pessimistic views that are linked to the broader societal uptake of digital fabrication, particularly AM.

Coming out of this review, I address frameworks which set these different claims into relation. I relate to them through critical theories of technology, which arise out of studies of technology (STS). My contention is that optimistic and pessimistic views on AM technology are symptoms of a technological *deterministic* view, which sees technological development as overriding both social relations and cultural values (Winner, 1983). In other words, it is a view which sees technology as linearly developed through continuous optimisation and refinement. I argue that such a reductionist view leaves little room for design, instead giving priority to those in ownership and in direct vicinity, through corporate development laboratories and its syndicate partners. Coming out of this analysis, I make an argument for a *non-deterministic* view on technology and its development, in which social involvement is made evident.

In the following section, I attempt to unpack some of the future visions and claims within relevant literature that are tied to discussions of digital fabrication, with a particular emphasis on AM and 3D printing. I primarily place the claims within two main categories – those that adhere to an optimistic future and those that incorporate dystopic claims. The reason for placing the literature within these positive and negative categories is to orient my discussion on theories as to how emergent technologies may be developed. As I explain in more detail later, these categorisations have in common that they are symptoms of a view on technological development in which complex political, social and cultural phenomena are not taken into account (Winner, 1997).

Following up on the review of the various social and technological deterministic claims that are being brought forward in relevant literature, I reflect on an alternative, non-deterministic view to arrive at a critique of AM.

2.4.1 A third industrial revolution – AM and optimistic claims

Technologically optimistic claims surrounding digital fabrication and AM are popularly brought forward by magazines on digital technology and lifestyle such as *Wired* magazine. Technological optimism is also a recurring rhetoric in canons of digital media, such as in Nicholas Negropontes *Being Digital* (1996). In his epilogue titled 'An age of Optimism', with a fair degree of foresight such as concerning the practices of Facebook in 2018, he discusses the powerful qualities of digital technology, which he argues will 'result in its ultimate triumph: de-centralizing, globalizing, harmonizing, and empowering' (Negroponte, 1996, p. 228).

The broad optimistic claim that is brought by the literature that I review in this section is that AM and its associated digital fabrication technologies will contribute to pivotal economic, social and environmental changes, sometimes referred to as a paradigm shift. The recurring moniker to these claims is typically that of AM as an enabler of a 'third industrial revolution' (Troxler, 2014). While such terms are often recounted in popular media, through magazines and newspaper outlets (Markillie, 2012), I focus principally on peer-reviewed academic literature.

Jeremy Rifkin's (2014) *Zero Marginal Cost-society* discusses the vast potentials of additive processes of digital fabrication, and its continuous strive towards refinement and improvement. As opposed to the current dominance of supersized, vertically integrated manufacturing models of today, Rifkin (2014) claims that AM enables a *horizontal* structure of distribution which comes with a vast amount of implications.

His review is specked with examples and comparisons between conventional manufacturing, and the vast changes that are presumably brought on by digital fabrication. Among other things, he (Rifkin, 2014) argues that the lack of human involvement in creating the blueprints which are fed into the fabricator makes it appropriate to think of the process as *infofacture* rather than *manufacture.* Rifkin (2014) also goes into the prospects of sustainability, which he claims are deeply rooted in the collective vision of those developing its technology. Rifkin's (2014) claims are anything less than profound; this is particularly reflected in his claim that 'In the next three decades, industry analysts expect that 3D printers will be equipped to produce far more sophisticated and complex products at ever-cheaper prices – taking the infofacturing process to near zero marginal cost' (Rifkin, 2014, p. 90).

Lipson and Kurman (2013) propose equally utopian claims by presenting an image of 3D printing as an influential driver of a vast range of emerging purposes and businesses. This view is given texture through a futuristic essay in which 3D printed materials are omni-present. The essay depicts a scenario in which everything we interact with, from the food we eat to the DIY organs we buy on the black market, is digitally produced. At the core of the book, Lipson and Kurman (2013) propose a list of principles where 3D printing is an advantage. Concepts such as zero skill manufacturing, fewer waste by-products and infinite shades of materials are a few of the many capabilities the authors argue that digital fabrication will bring.

Lipson and Kurman's (2006-2012) optimistic arguments must also be seen in relation to their research objectives titled Fab@Home, which made low-cost desktop fabrication kits available for hobbyists, inventors and artists. The Fab@Home programme, which was run at the time of writing their book, shared many of the principles and objectives as the RepRap[2] project.

Adhering to the third industrial revolution moniker, Troxler (2014) highlights a set of conditions which he argues need to be in place for FabLabs[3] to be a central narrative in the 'next industrial revolution' (p.1). Troxler (2014) notes that digital fabrication tools are not the cause and effect of this coming revolution, and compares it to arguments that that the previous industrial revolutions of the 19th and 20th centuries were in fact triggered by developments in communication infrastructure and energy generation. The coming revolution, he argues, is contingent on models of peer-production and polycentric systems being implemented more thoroughly by the maker movement (an agenda of which FabLabs are often seen as being a part). Here, peer-production is seen in reference to Benkler (2006), who describes it as an economical project, which, different from

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[2] The Replicating Rapid Prototyper, or RepRap for short, was initiated by Adrian Bowyer at the University of Bath in 2005 as an open-source hardware kit, in which key parts of the 3D printer could replicate itself, hence the word 'replicating' in its name.

[3] An initiative by MIT, FabLab is a network of communal laboratories that provide assistance and access to digital fabrication tools and skills. First set up in 2002, FabLabs are now found in all parts of the world.

firm- or market-based economies, is built on lateral relationships between larger fractions of the world's population.

While Troxler's (2014) reflections go beyond a mere projection of the current technical capacities of digital fabrication into the future, his underlying attitude seems evident. There will, in his view, at some point become a tipping point, where the developments of communication and energy systems will cause a greener, more sustainable revolution, and the maker movement will be at the centre of it.

In reflecting on the upsurge of technological utopias, Dickel and Schrape (2016) explore the semantic unfolding of popular media utopias through a case study of Web 2.0 and 3D printing. A central narrative that evolves with digital media, they claim, can be found around the *prosumer* figure (a combination of the terms producer and consumer; Dickel & Schrape, 2016). In the case of Web 2.0 (the social web), the prosumer is more accurately described as adhering to a virtual *media* utopia. The concept here is that the Web is an immaterial realm, detached from the physical constraints of capitalism and political power structures. The online prosumer is then seen as someone who takes advantage of the disruptive forces of online technologies by publishing their own videos, writing their own blogs and composing their own applications.

Similarly, the capacities of 3D printing regarding personal fabrication brings the concept of prosumption back into relevance. However, whereas the *online* prosumer is predominantly engaged with immaterial objects, the *3D* prosumer engages with physical material production. As noted by the authors, the popularisation of 3D printing resurrects the pre-existing notion of the media utopia that surfaced through Web 2.0. Only this time, the media utopia is very much physical in shape.

In summing up, the authors reflect on the utopias as a 'socially constructed' concept, highlighting the need to involve more real-world experiments (Dickel & Schrape, 2016):

> Desktop manufacturing utopias, as with the visions of the Web 2.0, point to a societal mismatch between the empirically experienced passivity of media recipients (or consumers) and a dominant notion of modernity: the idea, that individuals can, should, and wish to be productive and active participants in the shaping of their own society'. (p. 175)

Last, Greenfield's (2017) critique of AM comes from a different perspective. Looking at the technology from a top-level view, Greenfield's (2017) critique refers to two main themes: (a) the consequences AM technology may have in terms of *distribution* and (b) the value it brings through its ability to facilitate *iteration*.

While the perspectives of Rifkin (2014) and Lipson (2013) make it seem as if digital fabrication is heading towards mainstream dominance and that it is just a matter of clearing the table, Greenfield (2017) presents a reflected critique of digital fabrication. Drawing a slightly more nuanced image of its capacities, his view takes on a critique of the aesthetic, economic and sustainable issues related to contemporary uses of AM. As mentioned, his critique is formed around two central topics. The first is whether digital fabrication can be meaningfully *distributed,* referring to the fact that most of the materials with which we interact daily are complex *assemblages* of materials. These assemblages necessitate myriad manufacturing techniques and knowledge, from the cotton fibres that constitute our clothing to the cast-iron pots in our kitchen.

Second, Greenfield (2017) takes up the concept of *iteration* as a core principle to digital fabrication which comes with a set of upsides and downsides. While iteration serves as a useful capability for making rapid prototypes and things, it also makes it possible for people to create many *versions* of these things. Greenfield (2017) notes that if digital fabrication cannot be justified on the grounds of economy or even sustainability, it does so on the grounds of ideology. Referring to the concept of personal fabrication, he claims that the true novelty of digital fabrication is that it allows people to participate in artefacting and material production 'in a way that simply wasn't true in any previous era' (2017, loc. no. 125).

However, Greenfield's (2017) rhetoric relates to a flavour of social determinism, which is clearly articulated in the concluding parts of his discussion. In it, Greenfield (2017) reflects on the fact that 'we remain at the proof-of-concept stage: we now know that in principle, these things can be done. But all the social and intellectual heavy lifting begins now' (2017, loc. no. 1861).

2.4.2 AM and dystopian claims

While optimistic views can be brought about by assigning technology to the lead role in the transformation of new social structures, it also has the capacity to cast a darker, dystopic shadow on the picture. This view gives precedence to the unexpected outcomes of technological development, such as the formation of new power structures, misuse of privacy and online content, and the depletion of material recourses. More importantly, it strips bare any sense of freedom and individuality. As Winner (1997) suggests, the 'ominous signs' of dystopia are also apparent in the appeal to sociotechnical change that is often celebrated in the manifestos of 'cyberspace' (p. 1006).

Aligning with this manifesto format, Rourke and Allahyari (2015) deliberately indulge in the dystopian contributions that may arise through the adoption of 3D printing technologies. Their *3D Additivist Manifesto* (Allahyari & Rourke, 2015) call for a series of actions and must be seen as a call to challenge the scope of 3D printing. With a profound and satirical undertone, they declare that 'the world's splendour has been enriched by a new beauty: the beauty of crap, kipple and detritus' (Allahyari & Rourke, 2015, para 1). Following up on this, they call out for 'approaches, visions and speculations' which can 'counter, embrace, interfere and reverse-engineer' the perceived possibilities into a new 'radical notion of the 3D printer itself' (2015 para 6).

Their manifesto must be seen in relation to their edited book, titled *3D Additivist Cookbook* (2017), which includes a series of crafted objects, written reflections, toolkits and recipes that aim to inspire new uses to 3D printing. In the introduction, Rourke and Allahyari (2017) reflect on the need to collect the many ominous and dramatic projects, stating that 'To behold this compendium of recipes, toolkits, theoretical writings, and potential objects is to contend with an assembly of speculative worlds we have no desire to limit' (p. 5). In other words, their speculations are intentionally made disagreeable to mark a point.

From an architectural perspective on AM, Armstrong (2014) also voices concern for what she believes could become a potential hazard as 3D printing technologies develop further. Appropriately titled *3D Printing Will Destroy the World Unless it Tackles the Issue of Materiality,* the discussion centres around a critique of optimistic assumptions that are already tied to the developments of 3D printing. In this regard, Armstrong (2014) talks about materiality, and specifically *matter*, as a realm that is not solely lively but also malleable through participation and design interventions. Armstrong (2014) goes on to compare experimental 3D printing developments which aim to build temporary housing in devastated regions such as Haiti to that of the current state of desktop 3D printing, where oil-based plastics and high energy consumption is the norm. She forms a critique on how 3D printing needs to engage more with emerging cultural concerns and she addresses the issue of sustainable material consumption. She also reflects on how it needs to intervene with current material ecosystems in ways that are not yet possible with contemporary manufacturing systems. The objective, she reflects, is 'so that we can produce objects that in themselves forge positive environmental relationships such as carbon recycling or soil generating systems' (para 7).

Several of Armstrong's (2014) claims attach well to a deterministic stance to technology. The most prominent being in the title, where '3D printing' is voiced as an autonomous character. 'It must tackle the issue of materiality', she states, with 'it' referring to 3D printing. 'It' also reappears in the concluding statements, where Armstrong (2014) reflects that '3D printing *could* be a revolution in the making – but it's not *there* yet' (para 8).

2.4.3 A need for a non-deterministic view on AM

The literature reviewed in the previous section reflects some of the views of critics of technology. While it is not an exhaustive review, it provides a brief overview of some of the claims that are attached to digital fabrication. Specifically, the literature discusses an underlying rhetoric that is oriented towards the idea of technology as a rational, linear maturation process. Moving beyond such a reductionist view, it is relevant to ask – what is lacking in such a view of technology as a principal driver for social and cultural change?

In deliberating the influence of technological advances in CAD/CAM, authors Resch, Southwick and Ratto (2018) propose ways in which AM technologies might be put into better use. The text links to third wave HCI discourse (Filimowicz & Tzankova, 2018) and discusses ideals, liberatory values and pre-assumptions that are baked into visions of 3D printing technology. Specifically, Resch et al. emphasise the concept of de-naturalisation for clearing out biases about users and their behaviour towards conducting design.

As a grounding for their analysis, Resch et al.'s (2018) article investigates how historical affiliations to CAD/CAM and manufacturing play into the emergence of 3D printing. Tracing back to the post-war research programmes that developed CAD/CAM, certain key values are made explicit, which include reaffirming engineering authority, hierarchical ordering of tasks, erasure of expertise and liberatory technology – all values which partially coincide with the dominant AM-based uptake of 3D printing.

Following the historical scan, the article discusses case-work conducted with prosthetics practitioners. The authors stress the emphasis on collaboration with existing prosthetics expertise, which is still a practice dominated by manual labour. As opposed to seeing 3D printing as a replacement for their craft application of skill, such as the historical tendencies of CAD/CAM, the case describes how 3D printing can be usefully applied to supplement the prosthetists' skills.

The concept of 'de-naturalisation' to which Resch et al. (2018) refer is a recurring thematic in the field of STS studies and relates to Bijker's (1997) concept of closure/stabilisation (see p. 34), Feenberg's (2010) instrumentalisation theory (see p. 34) and the concept of sociomaterial assemblage (Suchman, 2007). The authors specifically refer to Jasanoff's (2012) concept of seeing emerging technological phenomena as 'through the eyes of visitors from other worlds' as a method for forcing oneself to look out of one's cultural sphere (p.6). Here, Jasanoff (2012) makes strong links to anthropology and argues that studies of sociotechnological development are positively complimented by methods of observation and participant-observation. These are means to countering the force of technological determinism.

2.5 Reflective Practice

My positioning of design practices, critical making and theories of sociotechnological change outlines a theoretical framework. This frameworking is done in order to argue for a practice-led design research which engages with phenomena around technological development related to AM. A key component missing of this framework is therefore the notion of *reflective practice*, which calls attention to the process in which practice may develop *tacit* knowledge around a subject.

In building towards an epistemological view of design in its own right, Schön's (1983) *Reflective Practitioner* deliberates the dominant division between theory and practice that exists in many professional disciplines. A central rationale is to provide an alternative to the dominant position of professional activity and practice as something which is 'made rigorous by the application of scientific theory and technique' (Schön, 1983, p. 21).

Coming out of Schön's (1983) view is the introduction to the concepts of *reflection-in-action* and *reflection-on-action*, which address the assumption that practitioners usually know more than they express. The principal concept, reflection-in-action evolves around the *tacit*, embodied knowledge, and the way in which it can help practitioners relate to *divergent* situations within their practice. Such situations are like those in which a jazz musician's improvised, yet tacit 'feel-for' their materials, allows them to listen and adjust to one another as they play. Second, the concept of reflection-on-action relates to a retrospective, indirect form of reflection on

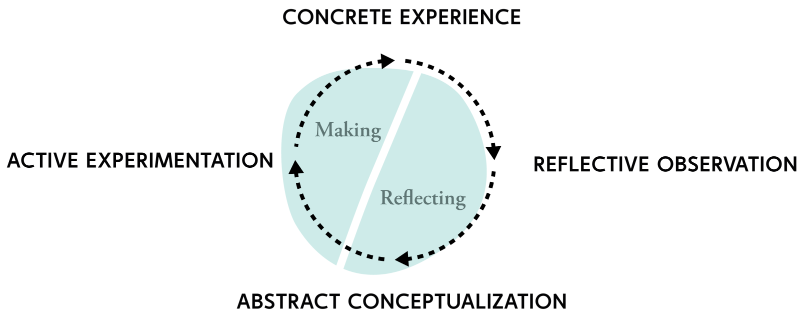

Figure 9 – Kolb's experiential learning cycle. Illustration: William Kempton, based on Kolb (1984)

the situations and divergent situations that occur within practice, and how it may inform new approaches.

Through Schön's (1983) concept emerges a view on design as an artistic and open-ended practice, rather than that of a scientific, problem-solving inquiry. Schön (1983) sees the process of the designer-practitioner as someone who 'shapes the situation, in accordance with his initial appreciation of it, the situation "talks back", and he responds to the situation's back-talk' (p. 79). This is also evident when he relates to design as a field of interest which includes 'policies, institutions, and behaviour itself, as objects of design' (Schön, 1983, p. 77).

Schön's (1983) concepts of reflective action are important for designers who engage in research, and particularly in strengthening the role of design research as a practice-based inquiry. However, Schön's (1983) version of reflective action can be criticised for lacking a *critical* perspective on the circumstances that shape practices (Crouch & Pearce, 2012). Usher and Johnston (1997) orient this critique of Schön's (1983) reflective practice to circumstances, ignoring that all practices, be they individual, institutional or system-wide, are inscribed; they inhibit certain social conventions, or *scripts,* which characterise the ways in which a certain practice acts. In order to engage with practice – one that is critically oriented – the practitioner needs to question the very conventions in which practice is acted out.

As a compliment to Schön's (1983) concepts of reflective action, I see my own reflective thinking as being tied to an iterative experiential cycle, between having concrete experiences and subsequently making abstract conceptualisations around them. This model of experiential learning is often referenced to in Kolb's (1984) experiential learning cycle (Figure 9), in which action, observation, reflection and theorising facilitates the continuous production of new knowledge. While I make further remarks on Kolb's (1984) experiential learning cycle in Chapter 4, specifically in relation to my own model for experiential learning and critical making, Kolb's (1984) model is also subject to critique. Specifically, this critique is forwarded by Miriam Webb (2003) who questions whether it is necessary to engage in all phases of the experiential learning cycle for learning to take place (see p. 96).

In the next chapter, I reflect on the methodological approach that I use in this study. I explain how I frame my design research project, how the use of both design and formal research methods play into it, and explore the data generated throughout the study to discuss more clearly the form of knowledge-making I am arguing for.

3 Methodologies, methods design practices and data

This study is a product design inquiry through which design is included as a critical, future-oriented practice (Celaschi & Celi, 2015) which investigates how technologies such as AM can be critically engaged with, analysed and constructed through making. The study looks to critical making (Hertz, 2015; Ratto, 2011) as a practice-led mode of investigation. This investigation is complimented by questioning assumptions and uses of technology through critical theories of technology (Akrich, 1992; Feenberg & Callon, 2010; Ihde, 2008).

In this introduction to methodologies, I explain my selection and use of research methods, design tools and design techniques. The purpose of the following methodological reflection is to position practice-led design research as a form of constructive inquiry in which analyses and outcomes are subjectively drawn from the situated practices that have been conducted. This epistemological view resembles a constructivist paradigm (Guba, 1990) as a form of inquiry that is subjective to its place, social context and practice of qualitative research methods, of an open-ended character (Denzin & Lincoln, 2018, p. 19). For example, in Figure 10 students are seen making chocolate with young visitors as a part of an installation at the Teknisk Museum in Oslo, Norway. As a qualitative inquiry, the study works with a variety of methods, techniques and processes. In doing so it takes on a number of objectives, views and interpretations.

My approach as a research-practitioner is multifaceted and involves generating research material, self-observation of my engagements, observing other practices and perspectives, and facilitating the making activities performed by others (Gray & Malins, 2004, p. 21). Through the analysis of research activities, the research project develops a *reflective* view *in* and *on* its practice (Schön, 1983). While it engages in individual and collective

Figure 10 – Student designers making chocolate on 3D printed moulds with teenagers during a temporary exhibiton at Teknisk Museum, Oslo. Photo: William Kempton.

engagement with 3D printing tools, the study establishes new routines and concepts for AM engagement which are based on the performed activities.

The research methodology, as Figure 11 illustrates, draws together research topics, research data, design tools and techniques, and formal research methods. They are presented in such a layered, circular model to give an overview of the topics of research, the kinds of data which I discuss, the practices I am involved in, and the activities involved in these practices.

Below, I discuss the use of qualitative research methods through a series of action verbs, such as *making, observing* and *arranging.* Describing these methods as actions allows me to relate them to the generation of qualitative research data, which includes curated installations (Figure 10), interviews and annotated design processes. These research data will be presented according to different descriptions, such as its intentions, employed techniques, gathering and involvement. The chapter culminates with a description of the role of the data and how they may be interpreted to explicate how I know what I know.

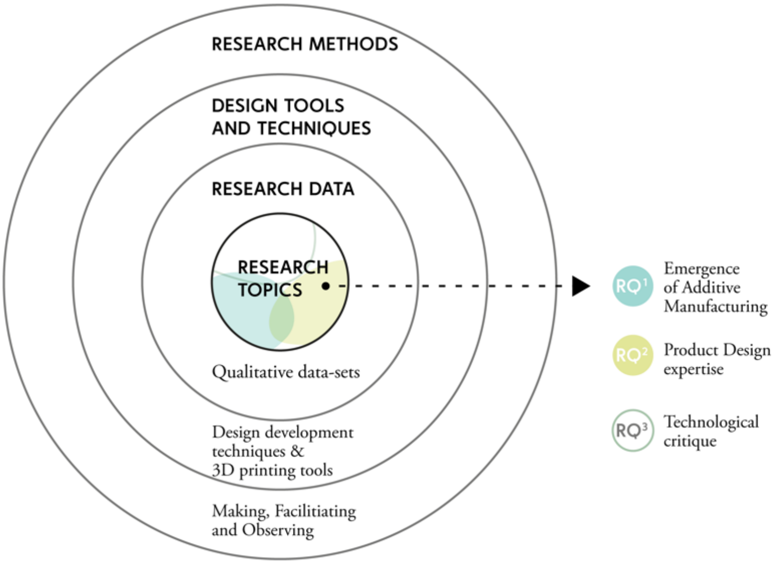

Figure 11 – A descriptive map of the relation between research methods, design tools and techniques, research data and research topics. Illustration: William Kempton.

3.1 Research methodology

Research methodology relates to a how an inquirer goes about finding out knowledge (Guba, 1990). In relation to design it can be seen as the study of the process of design, and specifically the approaches to which these processes are guided. (Cross, 1999; Sangiorgi & Scott, 2014). Design approaches may be described as critical, transformative or socially innovative, depending on the what the design intervenes on. A research methodology in design is therefore concerned with the choice of methods according to what the intervention is. When designing for social innovation, relevant methods might include imaginative services illustrated by short video sketches (Manzini & Coad, 2015, p. 138), or a set of experimental prototypes. Similarly, a participatory design might use video documentation as a technique for capturing various design proposals of a holistic *design space* (Westerlund, 2009).

In this study, research methodology guides my practice of design as a mode of developing knowledge around AM. Specifically, I have used AM as a platform for which to design and make artefacts which explores AM's characteristics and uses. In doing so, I have been practicing design as a way of knowing, which I argue is a step towards critiquing AM. In order to elaborate more fully on this, I will now discuss ways in which my research inquiry develops *through* design.

The making of physical artefacts and prototypes to draw an analysis, and through which to build new theories, is receiving renewed interest. In fact, the practice of designing as research inquiry is emerging through approaches such as *Research Through Design* (RtD). Increasingly popular venues for design-researchers are conferences devoted to RtD, which address the production of artefacts as constitutive of knowing and understanding. Approaches such as these is also the topic of major design journals such as Design Issues (Durrant et al., 2017). In popular terms, this approach to research may be referred to as practice-based-research or making-as-research. It recalls the need for design to form its own set of research methods as well as in valuing design practice as a mode of conducting research.

The reflective designer emerges as someone capable of conducting, reflecting on and analysing theoretical issues and concepts. One of its principal characteristics is to use and unpack design practice and activity into processes of building analytical knowledge. Through this process, the role of the designer-researcher is gaining increased attention in art and design institutions. The designer-researcher's ability to create links with the things design practitioners often do in a context of formal research becomes a matter of interest and concern.

Christopher Frayling (1993) examines relations between research as it is understood across different domains. While art and design subscribe to one version of research, fields such as chemistry or the social sciences subscribe to another. This gap is according to Frayling reflecting a need to provide new common grounds for which to discuss art and design as research, alongside that of sciences. Frayling (1993) deliberates on how different kinds of stereotypes and popular images emerge around characters such as the 'designer', 'fine artist' and the 'scientist'. While they are involved with different forms of activity, they share a common interest in *practice*. Frayling (1993) goes on to discuss how practice relates equally to the practices of science and literary writing as it does to the practice of art and design.

What comes out of Frayling's (1993) discussion is a distinction between three different forms of research practice which are conducted in art and design. Following on from Herbert Read's (1948) theories on the practice of art education, Frayling (1993) describes three distinct positions:

- Research into art and design
- Research through art and design
- Research for art and design

Research *into* design relates to the most common form of design and arts research, such as historical or aesthetic art research. The second position, RtD, implies practices such as material research, the development of novel techniques or action research. The latter position, research *for* design, relates more closely to the structured or unstructured searches conducted before or during the making of a particular design. It is the second position, however, that is of interest in the context of this exegesis as it sees research as a project that is done *through* design. As Frayling (1993) observes, the goal of such a position is not to create new artefacts per se, but a way to inform the designer-researcher through a process of generating new knowledge on a given hypothesis.

Considerable literature has addressed Frayling's (1993) research definitions, which have since amalgamated into new ones. In concepts such as research *by* design (Sevaldson, 2010), design is understood as a generative form of research inquiry, which performs across a rich layer of interrelated methods and positions. The goal of which is to go from an 'outsider perspective towards a more embedded insider (i.e. design) perspective' (Sevaldson, 2010, p. 25).

Similar to Sevaldson's (2010) model of design and research as something approached 'by design', Koskinen et. al's (2011) *constructive design research* links closer to design methods and techniques as a research activity. Here, constructive design is emphasised as a form of research 'in which something is actually built and put to use. Not only concepts, but materials. Not just bits, but atoms' (2011, p. 7). Physical artefacts and prototypes are here likened to embodiments of analysis, of which new theories can be built. From within interaction design practice, Einar Sneve Martinussen discusses practice-based design research as a layered approach, whose methodological motive is to 'make the technically invisible culturally visible' (Martinussen, 2015, p. 133). His work with Jørn Knutsen and Timo Arnall on *invisible* technologies, such as GPS, WiFi and RFID (Martinussen et al., 2014), can be seen as producing artefacts that are shared across mass media to build a cultural understanding and popular imagination to digital infrastructure.

As reflected by Stappers and Giaccardi (2017), RtD does not necessarily limit itself to a particular affiliation within practice-based design research. Rather, it can be understood as a way of articulating a *designerly* way of doing research, in which these designerly actions play a role in the development of generating new knowledge. While approaches to RtD are increasingly legitimised as a form of design research, it can be criticised for its lack of ‘rigour’ in its methodological approach (Zimmerman et al., 2010). Such criticism presented by Zimmerman et al. (2010) focuses on the ability, or lack thereof, of RtD to contribute to the development of theory, or high-level views on phenomenas under investigation. Based on interviews and case-studies of RtD practices, the authors (Zimmerman et al., 2010) present a series of challenges: the intended outcomes of RtD projects are often oblique, and there is a lack of standards for documenting an RtD process. In terms of theory development, the authors stress the need for RtD to build on and conduct a critical analysis of previous research. This need may be seen in contrast to views held by many RtD practitioners as creating ‘new’ work.

In Sevaldson’s (2010) discussion of design approaches to research, critique is also given on the contributions of traditional sciences to developing design research. As design research (particularly his own labelling of Research by Design) is vested in producing particular forms of knowledge and theory, based in and out of its own practice and reflection, it does not necessarily compare with theory developed in the ‘traditional’ sciences. Rather, Sevaldson (2010) suggests that designer-researchers should be more specific about which knowledge domains (or *sciences* as he phrases them), when ‘we talk about and what parts of design research we are comparing them with’ (p. 15).

I identify this research project as one which is grounded in knowledge that is developed through practice and design. This knowing, which I develop through making artefacts, becomes my basis of knowing about technological development. More specifically, I am developing a critical view on technology whereby I reflect through the very practice of engaging with it. As such I adhere to a constructionist position, which adheres to an overarching, constructivist paradigm (Guba, 1990).The constructionist emphasis and epistemology emerges through *making* – not only in relation to mental models, but with physical materials.

In the next section I will explain in more detail how I understand research activities from the basis of my own methodological view. These research activities and methods include *making*, *observing* and *arranging*, which I will elaborate on further in the next section.

3.2 Research methods

According to Creswell (2012), research methods can be seen a set of activities which involve the collection, analysis and interpretation of data. These activities are informed by a research methodology, which in turn has its grounding in a research problem. Within design, methods may be used to describe the activities a designer is involved with, from developing insight about users, through participatory workshops to wire-framing interfaces of a new design (Hanington & Martin, 2012). Similarly, within formal research the methodological position I take on is grounded in the constructed knowledge made through the practice of doing design. The distinction between design methods as a developmental activity, and research methods as an analytical and interpretative activity is therefore made by discussing them as design techniques.

My research position is situated in close proximity to design practices and activities that engage with AM tools. This is central to forming my critical reflections on their use and uptake. However, the research questions I aim to answer in this study call for multiple approaches and methods. Briefly put, I ask what are the emergent uses of AM, how these uses can be unpacked through design expertise and analysis, and why a critique of AM's technological development is relevant. In other words, I argue that design practice has the capacity to reveal both social and technical aspects of AM technology, which is important for debating the technological development of AM. The implication of this stance is the need to organise sets of research activities in close proximity to my own design practice.

3.2.1 Qualitative mixed-methods research

Following Zimmerman et al. (2010) and Sevaldson's (2010) argument that RtD needs to build on from existing research frameworks, this inquiry includes approaches to making, observing and arranging oriented towards analysis and interpretation. These approaches allow me to access the research topic through first-hand practice, in observation by others, and through arranging as a way of joining up practices with AM and literature that discusses its use. Coming out of these approaches I have collected different sets of data which will be discussed in later sections (see Section 3.4).

In the social sciences, mixed-methods approaches are principally used to collect different forms of qualitative and quantitative data. As Creswell (2012) points out, the gathering of both open-ended (qualitative) and closed-ended (quantitative) data allows for an analysis which spans both emerging and pre-determined methods. In particular, research programmes may make use of mixed-methods approaches as sequential, or even parallel modes, to confirm or disconfirm sets of data (Creswell, 2012, p. 269).

While the scope of this thesis is not to confirm or invalidate data, a mixed-methods research design may be useful in getting to know a research subject better, as different approaches may 'each provide further insight on the subject being explored' (Burton & Pedersen, 2014, p. 431). Through this mixed-methods framing, the thesis inquiry centres on the application of methods for making, gathering and interpreting qualitative data, which allows me to investigate emerging qualities and uses for AM.

The use of qualitative mixed methods as a research inquiry according to Greene (2007), is an activity which 'invites us to participate in dialogue about multiple ways of seeing and hearing, multiple ways of making sense of the social world, and multiple standpoints on what is important and to be valued and cherished' (p. 20). I emphasise the need for this RtD inquiry to employ methods in such a way that independent, qualitative interpretations are made evident through action. Specifically, I relate this to Norman Denzin's (2017) call for a critical qualitative inquiry, in which he emphasises the need to confront the 'audit culture of global neoliberalism' with a renewed attention to interpretive, critical and performative qualitative research (p. 1).

In order then to situate the project as one which attempts to not only see and interpret, but also create 'alternative moral points of view from which the problem, the policy, and the programme can be interpreted and assessed' (Denzin, 2017, p. 12), it is relevant to ask what the research activities do, how they are organised, and what they allow me to interpret.

My application of research methods includes activities commonly used within design practice, such as sketching, co-construction and prototyping (Kumar, 2012). I also apply ethnographic methods for studying different cultures of technological use (Blomberg et al., 2009). These are done in part through conducting interviews, and through making participant observations. However, as I apply such diverse methods holistically and in combination, I continue to discuss them below as action verbs such as *making*, *observing* and *reflecting*.

This shift towards methods as research actions, aligns with Celia Lury's (2018) proposal for presenting interdisciplinary research methods as instances of do-*ings*. Rather than seeing methods as simply being applied to a material, the use of action verbs such as those listed above implicate a performativity *with* the materials of my inquiry. Lury states that

'Approaching interdisciplinary methods as ways of giving a problem the form of the active present necessarily obliges the researcher to be attentive to the methodological potential of complex (spatio-) temporalities' (p.3).

In other words, approaching interdisciplinary and qualitative research as methods of engaging with a current situation places emphasis on the various ways in which new patterns or relations can be unfolded. How, then, do making, observing and arranging allow me to find a pattern to my research inquiry?

3.2.2 Making

The concept of making is fraught with subjective meaning and interpretation. As an action, making implies a sense of doing, that something is being made or constructed. Making is inventive: made things are products of different making processes, and are the product of innovation processes. Making can be understood as a recreational pastime, represented by the *maker* as a modern-day tinkerer who dabbles with electronic prototyping boards, engages in online communities for sharing blueprints or partakes in one of many Maker Faires across the world (Dougherty, 2012). Making invokes a sense of engagement, as it fashions matter into new meaning. Making is also aligned with practice. Fensham and Heller-Nicholas (2018) remind us that making participates in 'practice-as-research', as is often practiced in art schools. Here, emphasis is put on the iterative process of weaving ideas with production, be it the making of political structures or sensory objects.

In this thesis, the concept of making is raised on numerous occasions and concerns a diversity of meanings. The title of this thesis, *Unpacking Making*, can be read as making being an activity for unpacking-through-practice. It can also be read as an attempt to unpack what making is as research activity. A notable example of such a practice is the concept of critical making (Ratto, 2011). Lastly, making synonymous with the process in which a 3D printer fabricates, or *makes*, objects and artefacts from digital blueprints.

The notion of making I employ therefore lies in a tension between making as practical inquiry and making as a way of generating new perspectives. It relates to the acquisition of skill, or in addressing a particular phenomenon. As such it resembles Tim Ingold's notion of 'knowing from the inside' (2013). On the one hand, it actualises how design techniques such as sketching or low-definition prototyping can be used to engage with AM technologies such the 3D printer. On the other hand, it points towards a more profound sense of material-based experimentation which allows me to investigate, question and transform knowledge related to the technologies of my inquiry. Furthermore, Ingold's (2013) notion of making builds relations between the materials of our inquiry and our subjective image of it. It is the making of these images which allows us to learn. This is central to Ingold's (2013) argument that learning is not so much about learning facts *about* the world, as it is to be taught *by* it (2013, p. 2). More specifically, seeing the objects of this research inquiry as sources of knowledge for which one has to learn from releases any preconceptions and preconceived ideas about it.

3.2.3 Observing

Knowledge generated through practicing design and making is not immediately available in written words and figures; it requires approaches that centre on the activity of research practice. One central method is that of observation. Participant observation is a means to gaining interpretive knowledge, or 'thick description', of a particular research context (Geertz, 1973). Ingold (2013) recalls how observation and participant observation enables the enquirer to think *through* rather than *after* the object of inquiry (p. 11). Denzin and Norman (Denzin & Lincoln, 2018) remind us that 'individuals … are seldom able to give full explanations of their actions or intentions; all they can offer are accounts or stories about what they did and why' (2018, p. 53). Participant observation is a well-worn practice that I took up to approximate as fully as possible the perspectives of multiple, different participants in the wider research project. In the context of researching AM critically, it was also necessary to understand how qualitative research methods have been taken up by other researchers advancing critiques of technology.

In relation to design, conducting observations as a research practice has long-standing roots within disciplines such as product design and HCI. In the late 1970s, Xerox Palo Alto Research Centre notably started to employ anthropologists and other social scientists to get first-hand views of the challenges designers and engineers were having with their products (Blomberg et al., 2009). Lucy Suchman, who at the time worked as a researcher at Xerox PARC, recalls how contemporary photocopiers were criticised for being 'too complicated', even though the company advertised its Xerox 8200 copier as being a simple 'push of a green button' (Suchman, 2007, p. 9). Through videotaping, Suchman (2007) observed that rather than the lack of appropriate technical sophistication, users of the new photocopier had no foundation for interpreting the particular machine, which is characteristic of any new artefact.

Similarly, the work of this research project has been to observe and construct interpretations of a particular emergent technological process, which is arguably emerging as a field of expertise both within and outside of design. Using observational tools such as notetaking, photo recording and semi-structured interviews (Kvale, 1996), and participating in the various design activities conducted by myself and others, I have observed a manner of aspects related to the designerly uptake of 3D printing tools. I have looked at the ways in which professional product designers engage with 3D printers on a day-to-day basis, how student designers engage with the technical capacities of 3D printers, and how learning activities can be made to supplement 3D printing tools in the conceptual development of AM-focused projects. As such, observation represents a mode of reflective action on engagements performed within this research inquiry (Schön, 1983).

3.2.4 Arranging

Arranging stands for a particular form of action which creates a feedback loop between acts of making and modes of observing. Arranging can be seen as a process of putting to order, or making new compositions of individual parts, whether they are abstract concepts or the elements of an exhibition. As such, the act of arranging is supported by other sets of actions. To arrange is therefore to join up other acts of generating, collecting and experimenting, with the curating and composing of new structures (Bench, 2018).

Regarding this thesis, arranging as a research method and action holds a relation to the makings of my research practice and in the development of my scholarly work. As discussed earlier (see section 3.2.2), my adoption of *making* as a research method lies in a tension between the practice of engaging with design tools, and techniques as being a form of knowledge-making. The act of arranging, as seen in relation to this project, collects and visualises my research data, such as the curation of a series of installations with design students' individual crafted artefacts. It is important to connect such a view on arranging to the wider positioning of technology and practice.

Arranging is also relevant to understanding design within non-determinist theories of technology. Central to Feenberg's (2010) critical theory of technology lies his instrumentalisation theory, which seeks to explain how design creates bias in its process of arranging technology within a social context. All technologies, according to Feenberg (2010), can be broken down into a series of individual affordances, which he calls technical elements, which are free of constraints and relatively neutral. As these elements are arranged to form a device, such as a fridge or a car, they adhere to a specific social context and are necessarily constrained.

The reason for bringing in this theory is to draw attention to how *arrangement* constructs a vision to seemingly neutral components, and in doing so, creates bias. Just as Feenberg's (2008) instrumentalisation theory explains why a concrete device such as a fridge may have different characteristics according to the market for which it is made, my own arrangement of research data is the result of an attempt to make visible some of the affordances and characteristics that are found through the exploration of AM technology.

3.3 **Design techniques and tools**

In this section I focus attention to design techniques and tools, and how they enable the research project. As this project is conducted as a RtD study, the descriptions of design techniques, tools and research methods share certain overlaps. Specifically, when describing the research methods in the previous section, I made reference to the ways in which the project engages with *making* as a way constructing knowledge about the technologies of my inquiry. This section identifies and describes some of the design techniques and tools that enabled the making practice to be conducted.

Distinctions need to be made in regards to this research study, between technology, technique and tool. As mentioned earlier (see section 2.3) I link my holistic view on technology to a collection of cultural, technical and political aspects (Pacey, 1983). As such, it is linked to an overarching view in which technology is so embodied in our culture and everyday life that it can simply be understood as a 'way of life' (Winner, 1983). Technique, as an aspect of technology, relates more specifically to the instructions or recipes for performing an activity (Mokyr, 1996). As opposed to technical artefacts, techniques represent the technological know-how which allows us to talk about the activities of a practice. Without any such know-how, there would be no practice to discuss, and all artefacts would meaningless.

Tools, in contrast, are the technical artefacts which are intentionally man-made, that possess a set of materialities and has a distinct form (Franssen, 2008). This is not to say that tools are exclusively physical. Technical tools, particularly those that make up AM, are compositions of both digital and physical matter. Equally so is the materiality which makes up a tool, which I have I have discussed earlier as relating to the characteristics of a tool (see

Figure 12 - Students engaged with prototyping a cocktail shaker from two ordinary drinking glasses. Photo: William Kempton.

2.3.4). These characteristics are relevant for design, as they enable the development of technique.

3.3.1 Product design techniques

It is necessary to discuss technique as the activity which enables the use of a tool. Furthermore, technique is what enables me to conduct a research activity. Technique talks about skill and practice, which in a product design context can be tied to the activities of transforming abstract ideas into commercial products (Lawson, 2006). In relation to my research inquiry, product design technique is centred on linking the boundary between abstract concepts and tangible form (Ratto, 2011). To facilitate this transition, product design practitioners rely on different sets of approaches to conceptualise, prototype, sketch and convey their ideas. Figure 12 illustrates how a design practice might involve techniques for creating mock-ups and prototypes. Here, a student is depicted attempting to create a cocktail shaker from two ordinary glasses and a white, plastic component. The rigidity of the 3D printed PLA plastic, typically used in desktop 3D printers, requires the design to parametrically adapt to different glass sizes. Without any such technical know-how of both CAD tools and the properties of PLA, the designer would not necessarily arrive at a satisfactory result.

While my understanding of product design techniques is not limited to the activity of prototyping, I see it as a technique which is particularly relevant for the development of theoretical concepts which will be discussed later in Chapter 4. Along with product design techniques such as sketching, interviewing, photographing, video-sketching and participant-observing, I see the incremental activity of prototyping as a particularly relevant technique for facilitating a distinct process of learning about, and consequently knowing on AM technology.

3.3.2 3D printing tools

Techniques such as prototyping are relevant as ways of engaging with 3D printing tools. The ability to iterate is a defining characteristic of 3D printing tools. This I recounted in my review of AM (see section 2.4.3), as one of the very core capacities of 3D printing and digital fabrication tools in general. Furthermore, it is the ability to create iterations of things, not only in shape and form, but as distinct *versions*, which is advanced in the concept of AM.

The concept of iteration is likened by Fensham and Heller-Nicolas (2018) as a process of weaving ideas with production, and relies on a feedback loop between conceptual thinking and active experience. While I will tie in this characteristic later with experiential learning theories, it is relevant to mention here that 3D printing tools are also constituted of distinct phases.

The initial *pre-processing* phase involves preparing and readying CAD models into formats that are readable to the 3D printer (often referred to as slicing). Commonly, 3D printers are bundled with software applications that allow users to prepare their files and relay them to the fabrication device.

The *fabrication* phase centres on the process which produces physical matter. The different processes that make up 3D printing require specific building materials, which may have vastly different capabilities. While solid-based processes such as FDM (commonly used in desktop 3D printing) apply layer upon layer of plastic polymer through a heated nozzle, liquid-based processes such as stereolithography (SLA) rely on solidifying liquid polymers in a layerwise fashion using light. Powder-based processes distribute layers of fine-grained plastic, metal or gypsum granulates onto a surface which are bonded together with direct energy or adhesive.

Last, the *post-processing* stage involves the various stages of curing, rinsing and preparing fabricated artefacts for subsequent use and implementation. The aim of providing this brief overview of tools and techniques is to clarify

Figure 13 –Design students evaluating a set of fabricated artefacts that are in display in a course exhibition. Photo: William Kempton.

the uses of terms such as 3D printing tools. This clarification is relevant as I continue to talk about research data in the next section.

3.4 Research data

The research data that will be presented in this section is explained in order to make sense of the activities I have been engaged in throughout the research project. The data is qualitative, in that it allows me to advance my perspective of how participatory activity illustrates an emergent use of AM. Further, by exploring the qualitative data through descriptions and illustrations, it helps me advance my own theories on how emergent uses develop new knowledge to AM. As such, my view on qualitative data is akin to data which 'generates us as we generate them and produce shards of knowledge that elude categorisation' (Nordstrom, 2013).

Research data is partially generated from within the digital fabrication lab found at the school campus, as well as including engagements within and outside of teaching at AHO. Data is generated through my own practice, and in observations of professional design experts. The AM research lab was founded in the late 1990s as a collaboration between AHO and notable industrial partners. Since its founding, students have been involved in research initiatives, including the operation of AM equipment and the

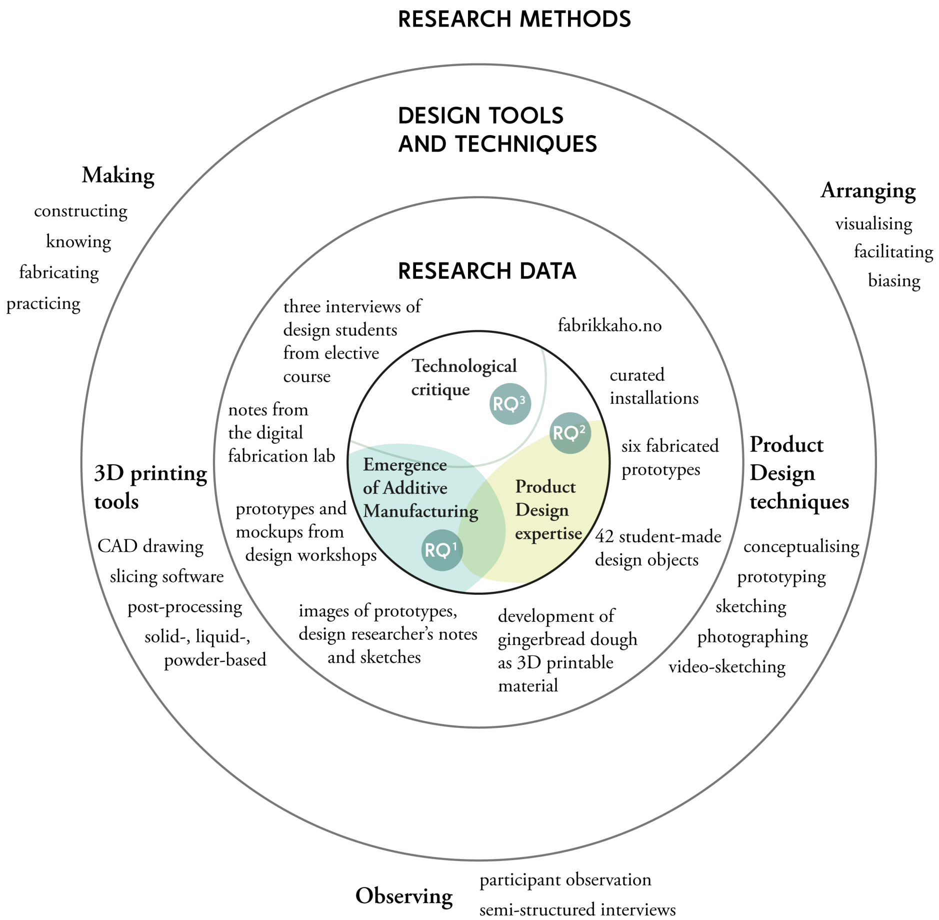

Figure 14 – The relation between research methods, design tools and techniques, research data and research topics. Illustration: William Kempton.

design and construction of 3D printed artefacts. As a digital fabrication lab within an educational setting in a design school, the distinction between research and educational purposes is often blended (Celani, 2012). As a closed lab environment that is fully equipped with 3D printing tools, the majority of the day-to-day work currently relates to making prototypes and models for students and staff. As such, the role of 3D printing as an RP tool is relevant because designers and architects often need tangible models for their digital creations.

The digital fabrication lab at AHO is largely relevant to this research study because it is the location of many of the situated practices and making experiments which were conducted throughout the study. It is also where many of the workshops and students' courses were held. As such, it can be seen as a *Living Lab* (Pallot et al., 2010), in which staff, students and researchers form relationships outside of the conventional design studio.

3.4.1 Presenting research data

As the product of the different research methods employed. The research data acquired in this study is diverse. The data comprises curated installations, digitally fabricated artefacts, annotated design processes, participant observations, interviews and an online repository which have been generated, sorted out and analysed. The Figure 14 illustrates the relation between research activities and research data.

Seen in relation to the overall research objective, the data can also be seen as attempts to grasp themes the project takes up, as well as approaches for proposing the research questions that form the themes. To recapitulate, the first research question seeks to understand the contemporary and emergent uses of AM and emphasises the need to observe the uses and techniques. The second research question speaks towards the design expertise and engagement, while the third question draws critiques and analyses from the engagements which have been performed.

The application of research methods therefore involves generating, collecting and revealing the data, which consists of tangible and intangible materials. The documentation of design activities conducted throughout this project are grounded in the use of design tools and situated practices which are integral to an RtD approach. Coming out of these design activities are not only the artefactual outcomes made by myself and others, but the spaces in which they are presented, and the way in which they are visualised. The summary of the data shown in Table 1 is therefore organised according to selected methods and the types of data they produced. The table also describes what the data are, why they are made, how they are stored, where they are located, where they are discussed and what they do for the research analysis.

Table 1 – Summary of the research data

Type	**1 Description** *How was the data constructed?*	**2 Intention** *How was the data conceptualised?*	**3 Technique** *How is it obtained?*
Curated installations	Four curated installations of design projects made in the 'digital fabrication' elective master's course	To create a public space in which different digitally fabricated materials, prototypes and artefacts are visible	Providing knowledge and technical recourses for students' individual design approaches
Digitally fabricated artefacts	Forty-two student-made design objects (from 3D veneered computer mouses to digitally fabricated music LPs)	To observe students' engagement with digital fabrication tools	Using design tools and techniques from the digital fabrication laboratory
	Six fabricated prototypes (silver ring, stencil, 3D veneer mould, pen holder, Inuit inspired sunglasses, gingerbread house)	To reflect on research practice, and conceptualise uses of AM technologies	Designing tools and 3D printing processes
Annotated design processes	Development of gingerbread dough as 3D printable material	To explore alternative materials for 3D printing	Combining novel 3D printing tools and modifying a gingerbread dough recipe
Participant observation	Images of prototypes, design researcher's notes and sketches from three visits to professional design studio	To understand how practitioners incorporate digital fabrication into development strategies	Conducting semi-structured dialogues based on visits to design studios
	Design researcher's notes, pencil sketches, cardboard prototypes and mock-ups from three design workshops	To observe student work in conceptualising AM products	Organising critiques and tutoring students
	Design researcher's notes from the digital fabrication lab at AHO	To provide operational knowledge on AM	Accompanying staff at the digital fabrication lab
Interviews	Three interviews with design students participating in 'digital fabrication' master's elective course	To provide individual feedback on the course curriculum	Making transcriptions from interviews
	Semi-structured interviews with the director of a makerspace	To discuss the challenge of teaching digi.fab. to elementary school students	Conducting informal visits to makerspace
Online repository	Online pop-up store for 3D printed phone cases	To create a service to sell small quantities of artisanal phone cases	Using online payment services and design tools

4 Gathered *How is it stored?*	**5 Position** *Where is it located?*	**6 Involvement** *Who is involved?*	**7 About** *Where is it discussed?*	**8 Function** *What does it do?*
Private image repository and online blog (designresearch.no)	AHO gallery 2015, 2016 and 2017, and Teknisk Museum, 2017	Active participation (facilitating brief, workshop and installation)	Publications 2 & 4, and conference paper (Killi et al., 2017)	Creates a space for technical learning and active experimentation
www.designresearch.com/projects/Williams-phd	AHO Digital fabrication lab, 2014-2017	Moderate participation	Publications 2 & 4	Reflects on utilities of 3D printing through design exploration
Private image repository	AHO Digital fabrication lab, 2013-2017	Complete participation	Publications 1 and 2	Provides imagery and links produced artefacts to areas of AM use
Notebook sketches, online video (youtube.com), blog post (medium.com)	AHO Digital fabrication lab, 2016	Complete participation	Publication 2	Challenges perceptions of AM as a process for making usable artefacts
Annotated video recordings, sketches and field notes	Oslo-region, 2015-2016	Moderate participation	Publication 3	Gives insights into developmental application of AM
Private image repository, Fabrikkaho.no (now offline)	AHO 2014, 2015, 2016	Active participation	Publications 1, 2 & 4	Provides situated knowledge about students' design expertise
Design researchers' notes, images	AHO 2013-2018	Active participation	–	Informs the design researcher on the operation of AM tools
Private repository	AHO 2016 & 2017	Passive participation	–	Corresponds oral feedback with feedback from survey conducted by AHO admin
Design researchers' notes	Teknisk Museum, Oslo, 2015	Passive participation	Publication 2, (Kempton, 2016)	Observes communal makerspace
Fabrikkaho.no	–	Active participation	Publications 1 & 2	Shifts attention towards the ideative capacities of student designers

3.4.2 Revealing the data

Table 1 presents an overview of the research data accumulated throughout the project. The overview is organised according to the different types of data and gives a description of what the data constitutes. While the data summarises my research activities, there is no contextualisation to how it develops the research study. Therefore, in the following section, I unpack the data further and give an account of the data in the context of a situated research practice. Rather than discussing each data entry in successive order, I present an overarching description of the data and intentions for making it, followed by the tools and techniques that have been involved, before linking the data to each research publication. I then close with a discussion of the function that the research data serves, what the data do as research, and how the data enable me to know what I know.

In the previous section, I explained the location and selection of research methods from diverse fields. While methods such as prototyping, sketching and co-constructing come out of product design development, I drew up an interdisciplinary approach to the methods which are described using action verbs. Therefore, no strict distinctions are made to explain the making of the research data, as they are often a result of diverse methods. For example, the workshops conducted with master's students employed many diverse methods, such as prototyping, artefacting, notetaking and photography.

Throughout this research study, I gathered diverse sets of research data through different research methods, which have been used within and outside of the different situated practices entailed in the study. Aside from being different in shape and form, the data are also a result of different intensions. Whereas a dataset can be described according to what it is, the intentions of the data are articulated through asking the question of why it is made.

3.4.3 Facilitating student engagements with digital fabrication

Several sets of data describe the work which includes curated installations exhibited at the AHO campus between 2015 and 2017 and at the Teknisk Museum in Oslo. The installations were made as a part of the 'digital fabrication' elective master's course, which aimed to give masters of design and architecture students the resources and techniques to engage with digital fabrication tools (see Table 2). The first part of the course was concerned with building the necessary knowledge and skills to operate the different

Figure 15 – Exhibitions spaces and AM artefacts in public view. AHO gallery 2015. Photo: William Kempton.

digital fabrication processes (CNC, laser-cutting, flatbed routing, 3DP, SLS, SLA and FDM printers) that are available in the digital fabrication lab at AHO. The second part of the course turned attention towards a critical reflection through articulating material concepts and prototypes.

Table 2 – Overview of laboratory facilities and participants

Facilities	AHO Digital fabrication lab (3D printers: SLS, SLA, 3DP, FDM & LDM) AHO Plastics lab (CNC milling, laser-cutting, flatbed routing) AHO Gallery space and Skaperverkstedet at Teknisk Museum, Oslo
Experts	Digital fabrication technician, PhD researcher & professor of industrial design
Course format	6 ECTS points, 11 3 hr events & a 5-day workshop week

Having developed an elementary understanding of the digital fabrication techniques, the students were encouraged to form their independent understanding of its qualities and capabilities. The students were encouraged to play on cultural and technical activities, such as music listening, woodworking, robotics, home furnishing and food consumption. These activities were then presented in an exhibition format, which was curated in collaboration with the course responsibles.

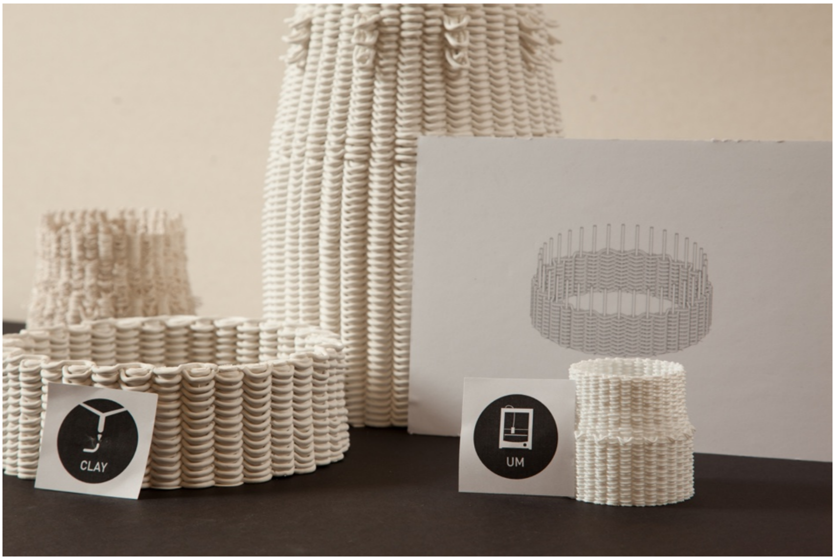

Figure 16 – Models and prototypes of an attempt to weave clay using a desktop-sized 3D printer. Design by Jon Bjørn Dundas Morå; Photo: William Kempton.

Each year the design activities were organised into specific themes. In 2015, when the programme was first run, students were tasked with choosing a pre-made material with which their design had to engage. Chosen materials ranged from leather patches, wool yarns and motor vehicle springs to wax candles and fishing rods. In the year that followed, students were asked to provide a theme, which later turned into a series of themes ranging from 3D printed clay weaving to music consumption. The third time the course was run, in 2017, the overall exhibition, titled 'Timelines', was set for each project to show different interpretations of time and scale through three exhibited artefacts. While some students chose to visualise their fabricated artefacts as a linear product development timeline (see Figure 17: Erlandsen's 3D veneered computer mouse), others used the concept of time and scale to show artefacts such as 3D printed joinery that could express movement.

The aim of creating the exhibitions was principally to make visible to a public audience the new materialities which are conceptualised as student designers engage with digital fabrication tools. As the students were tasked with combining digital fabrication with existing materials and techniques available to them in the wood-, metal- and plastics labs, a new range of materialities could be presented. While some projects sought to supplement existing techniques with AM, such as metal casting (Figure 18), others explored the characteristics of the 3D printed materials. The project shown

Figure 17 – Artefacts, tools and materials in the process of designing. Designs by Hans-Martin Erlandsen; Photo: William Kempton.

in Figure 16 illustrates how a desktop 3D printer is repurposed to print stoneware clay. Inspired by various weaving techniques, the architecture student set out to capture the open, mesh-like texture of woven artefacts such as wicker baskets.

Table 3 – Overview of the courses held

2015	14 students (12 design / 2 architecture students) Title: 3DX14
2016	11 students (8 design / 3 architecture students) Title: Digital is the new physical
2017	18 students (16 design / 2 architecture students) Title: Timelines

Figure 18 – Students' attempts at making aluminium casts using both FDM-based and 3DP processes. Photo: William Kempton.

The aim of curating an installation around the individual student projects was also to have the students present the outcomes of their design activities. As each project started off with a research question, the students were required to present both successful and unintended outcomes of their experiments. The project shown in Figure 18 combined traditional metal casting processes with AM for learning about the process and investigating its aesthetics. Aside from presenting material samples and moulding tools, by-products of the casting process were also shown (lower right-hand corner) along with the self-made furnaces and protective clothing required to perform the casting.

In all, 42 design projects were presented in the three exhibitions which were shown during the three years that the course was run (see Table 3). Aside from acting as exhibition materials to see the diverse contexts and tools which could go into digital fabrication, each endeavour also gave insights into how a learning process could be developed. As the participating students had different levels of prior knowledge on how to engage with digital fabrication tools, it became evident that the pedagogical process had to facilitate both technical knowledge about the processes involved and a contextual understanding of it. While I had performed my own observations through notetaking and dialogue with students during the semester, I conducted a number of semi-structured interviews with the course participants after the course ended to obtain individual feedback on the course curriculum for making possible changes.

3.4.4 Observing and interviewing participants in the elective courses

My initial observations led me to assume that course participants were motivated to further their existing knowledge of digital fabrication to engage critically with its tools. Interviews with students, however, pointed to a contrast in terms of the participants' prior experience and their disciplinary interpretation of what constituted AM and 3D printing.

For student A, who was doing a master's in service design, initial concerns were simply to understand how to realise a simple geometry in a CAD application, before passing it onto a 3D printer: 'There's some people who knew all of these different [3D printing technologies] … I didn't know any of them. There was not a single technology that we touched I had … ever touched before' (Student A).

Rather than seeing her engagements as opening new possibilities for how to use digital fabrication tools, she likened her experience to a process of filtering. As she felt she was running up against the limitations of not knowing, she focused on stoneware clay printing as her medium-of-choice to present in the exhibition. While her initial intentions were to learn how to print with clay and fire it in a kiln, her focus soon shifted towards questioning what kind of things she could make with it, and how she could employ other techniques she already knew.

Similarly, the challenge of not having extensive prior knowledge about CAD drawing, shifted other students' focus on how to engage with specific digital fabrication tools. Student B, who has a background in furniture design, saw his prior knowledge of handcraft, particularly woodworking, as a point of departure.

> I tried to use my complete lack of skill in [CAD] drafting as a creative boundary…. And I very quickly learned that you don't need to be an expert in digital modelling to actually have fun and explore interesting questions with 3D printing. (Student B)

When asked what are the principal issues for someone to engage with digital fabrication as a tool, the student responded,

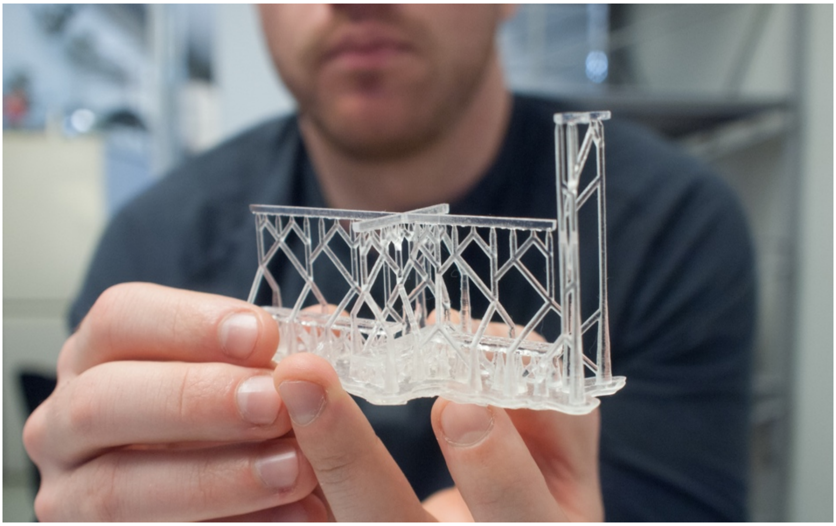

Figure 19 – Student B presenting a model using the support structure as a part of the material exploration. Photo: William Kempton.

> Fundamentally my main barrier was this perception that I needed much better computer drafting skills than I had, which isn't true. I think that to use 3D printing to its full potential, it certainly helps to be able to draw exactly what you want very quickly, but it's definitely not necessary…. There's ways of getting around it. I mean, you could get somebody else to do a drawing for you based on a sketch. But in the class, I try to use very simple drawings as tools to experiment with the media of 3-D printing itself, rather than experimenting with digital drawing as the media. (Student B)

To exemplify what the student intended by exploring the 3D printer as a medium, he presented the model he made while learning to use a liquid-based SLA 3D printer (Figure 19). The digital model consisted of two squares and two crosses made in Rhino (CAD software) which were used to generate a set of support structures that the 3D printer slicing software generated. The algorithm created the support structure which branched out at 45 degrees and tapered in a specific way to create the model seen in Figure 19.

Other students indicated that they had specific preconceptions about how to use digital fabrication. Student C, who has a background in interaction design, saw the open-ended tasks given throughout the semester as a chance to 'break', or challenge the tools and techniques of the various digital fabrication processes: 'It was interesting for me … to break it [figuratively speaking] or, like, see what the limitations are against the limits, not break the tool but kind of break them apart' (Student C).

The student, who had prior experience with desktop 3D printers, used the course's exhibition format to craft a series of abstract, geometric forms which had been created using script-based modelling such as OpenSCAD. For him, the 3D printer served primarily as a tool for replicating his scripted inputs.

> Having the programming background kind of let me think of these tools as just computational output. So, because they can do, like, replication so well, that means that I can do kind of more complicated things without being worried about it, like, you know, necessarily failing, or just pushing things further. (Student C)

3.4.5 Exploring alternative materials for 3D printing

The facilitation of students' engagements was intended as a way to observe and reflect on different approaches and engagements with digital fabrication tools. It also served as a way to conceptualise new learning approaches to AM based on the technical learning and contextual experimentation which the students conducted.

Engaging with AM tools has also been a part of my own research-practice. It has allowed me to reflect on ways in which to engage with a 3D printer, conceptualise uses of AM technologies, and explore alternative materials for 3D printing. One of the particular engagements that came out of my research-practice was the development of gingerbread dough as a 3D printable material (Figure 20).

Baking gingerbread has a long-standing tradition in Norwegian homes. It is a ritual which is usually performed during the Christmas season and is pursued by children and adults alike. While some people are content with cutting out and decorating their gingerbread biscuits, others take a craftier approach, which usually involves making gingerbread houses. The tradition of making gingerbread houses remains strong among Norwegians, spawning communal activities such as the making of gingerbread villages, or 'pepperkakebyer', in public squares such as in Bergen, Norway.

The relation between the gingerbread house and this research project started after initial experimentations with a liquid deposition modelling (LDM) 3D printer. After using the tool with the prescribed clay materials as a part of the digital fabrication course at AHO, some of the students confronted me

Figure 20 – Inspired by Borgund Stavkirke, a Norwegian medieval stave church, the 3D printed gingerbread house stood 22 cm tall. Photo: William Kempton.

with the following challenge: What happens if you replace the stoneware clay material with gingerbread dough?

While the idea seemed straight forward, the initial trials told a different story. I quickly realised that gravity would be a decisive issue. Not only is gingerbread dough a viscous material, but it needs to be baked in an oven to be edible. Those who engage in gingerbread house-building will know that structures are best glued together with prebaked pieces of gingerbread, much like a prefabricated house. However, as this is not how I intended to build my gingerbread house, I needed to develop my own additive process.

As Figure 21 shows, a variety of iterations were made before developing a satisfactory process. Three steps were necessary to successfully conduct the printing process: (1) mixing a sufficiently firm dough recipe; (2) modifying the 3D printing tool to extrude dough in successive layers; and (3) creating a suitable, printable design.

Combining ingredients to form a unique recipe became the initial focus. In addition to adding corn starch to the initial recipe, it was quickly decided to add alcohol to the mix. As alcohol evaporates in room temperature, the hypothesis was that this might harden the deposited material. Finding the right consistency, however, proved to be a challenge – too much liquid and

Figure 21 – Many attempts were made at refining both the gingerbread dough and the technical process itself. Photo: William Kempton.

the structure would deflate. Too little and material deposition would be insufficient.

The 3D printer, a WASP 2040 modified with an LDM extruder, was used to deposit the gingerbread dough material. As the deposited material would often deflate after reaching a certain level, the extruder mechanism was modified to include a heated nozzle. While this is common practice for melting and extruding plastic in conventional 3D printers, it was added to the gingerbread 3D printer to evaporate the alcohol more quickly and to allow the corn flour to harden.

The design of the gingerbread house was based on Borgund Stavkirke, a medieval Norwegian wooden stave church. As the structure had few overhangs, it proved an ideal structure to 3D print. Earlier iterations (Figure 21) were made hollow, but the final structure would require additional internal supports, as can be seen in Figure 22. While the printed structure stood 22 cm tall, the weight of the dough and the process of baking in the oven took its toll on the house, making it shrink considerably.

3.4.6 Observation of public interpretations

To attract attention to the gingerbread project, it was advertised on social media through an instructive video (Kempton, 2016a) and as DIY instruction (Kempton, 2016b) as the 'world's first 3D printed gingerbread

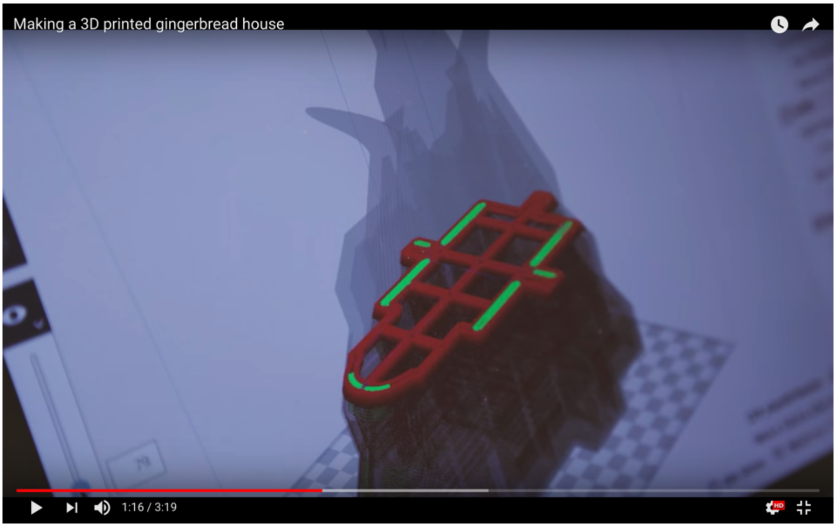

Figure 22 – The process of making the 3D gingerbread house was documented and shared in an online video. Video: Alexandre Chappell.

house'. A video provided the viewer with a recipe and visual instruction on the process, while showing the making-of process of the 3D printed gingerbread house. Published a week before Christmas 2016, the video and accompanying images soon caught attention and were shared across national and international blogs and news sites. Consequently, comments on the project soon started to accumulate. While a broad amount of interest can be seen as curiously positive, a few elaborated, critical responses were also voiced. The comment below (Figure 23), written by 'keal' on the nrkbeta.no website, reflects a particularly interesting view because it addresses the potential downsides of involving digital fabrication into our everyday life.

> So now we are replacing the Christmas activity 'draw and build gingerbread houses with the kids', with 'sitting and watching a machine do what we previously thought to be the best part of the arrival of Christmas'.
>
> Technologically impressive, but what's the point, other than being technologically impressive? How does this improve on the traditional 'advent experience'? Well, best case we can brag about how 'my machine makes more fancy gingerbread houses than your machine, so there you go!' Christmas activities will be judged by those who have the fanciest machine that they can sit and watch…

Figure 23 – Comments and critiques on nrkbeta.no, following the online publication of the 3D printed gingerbread house project. Screenshot obtained from nrkbeta.no.

> While it an impressive technology, it's not really these kind of Christmas activities I strive to enact to evoke a nostalgic, romantic Christmas feeling. But maybe I'm just old fashioned. (keal)

The comment starts out by voicing a concern for the fabrication process, which in user keal's opinion will ultimately create a future situation where the builder of the gingerbread houses is left passively watching the machine do the work. He then asks how this will improve the traditional 'advent experience'.

While the comment can be dismissed as a mere nostalgic reflection (in fact 'keal' mentions it himself), it nevertheless points towards a conflict of interpretation of the role of digital fabrication technology, which is entirely different to the position I took. As mentioned earlier, the ambition was to create a use for the liquid-extruding 3D printer which could visualise ways in which 3D printing could be creatively used within an everyday context. However, the commenter in question perceived the outcome as a threat to his own idea of a traditional Christmas activity.

This conflict of opinion proves to be relevant for later discussions on how technology is perceived and in initiating a critique of how technology might be assessed. As I have discussed in my review of technological theory (see section 2.3.2), it brings into relevance the concept of technological determinism, in which technological agency overrides social agency. As the commenter interestingly points out, the introduction of robotic tools such as a digitised gingerbread fabricator in the kitchen, would potentially challenge existing ways of performing this Christmas ritual. Yet again, it opens for ways in which to consider how such a ritual might be designed if the goal of the project itself is to maintain a sense of purposefulness in Christmas activities.

3.4.7 Observation of design experts

A number of observations on AM uptake were conducted with practicing design professionals in the winter of 2015/2016. The sites of these observations were product design offices in the Oslo region. The selection of the three sites were made based on offices' known engagement with 3D printing tools as part of their product development cycles. The observations centred on a series of products, prototypes and mock-ups, with the topic of discussion being the subjects' use of digital fabrication into development strategies (see Table 4).

Table 4 – Overview of observations of design experts.

Sites	Three product design offices in the Oslo region (2–8 employees)
Duration	1–3 hours
Methods	Semi-structured interviews, timeline mapping of development processes, video/image recording, field notes
Topics of discussion	Development and production of a vibrating watch, a solar lamp and phone charger, snowshoes and an ergonomic ski-pole grip

During the first visit, discussions centred on the development of a novel wristwatch which indicated the time by vibrating in five-minute intervals. The subjects' product had initially been made by the designers using online 3D printing services and a local printed circuit board (PCB) board manufacturer. In later versions, the product had been redesigned for easing their assembly-time and improving durability and use.

While the first visit focused on observing the designers' self-production of additively manufactured artefacts, the second and third office visits were primarily engaged with consultancy work. At these locations, discussions centred on how 3D printers were used to facilitate the making of prototypes for the development of form, ergonomics and feasibility of production. Product development processes included a snowshoe, an ergonomic ski-pole grip, and a solar lamp with integrated phone charger. Each project included a series of incremental prototypes which were brought out of storage, analysed and subsequently configured in relation to each other.

Figure 24 - A timeline mapping of the development of an ergonomic ski-pole grip. Photo: William Kempton.

All three visits were led by an initial mapping session in which the interview participants were asked to arrange their prototypes according to a developmental timeline (Figure 24). Using a pen and paper, the participants were asked to annotate each prototype with how they were made, what purpose they served and whether they were successful. Each interview was video recorded to support to my notetaking, and photos were taken of each timeline mapping for later analysis.

3.4.8 Function of the research data

Through this section I elaborated on the methods used, the actions taken, tools and techniques involved. Together, they constitute the qualitative data generated in this research project. Specifically, it was through documenting and describing these research do-*ings* that I developed my initial notions of design practice and making as a learning process. Particularly in the context of this inquiry, which looks at emergent uses on AM, the qualitative data has enabled me to advance the idea of learning as a way to facilitate the concept of making-as-knowledge in relation to a study of technology. As such, the data has facilitated a dialogue for which to join relations to participation and technological development, which this thesis goes on to analyse.

The initial attempts at hosting students in the AHO digital fabrication lab were motivated by creating an environment in which 3D printers and tools could be accessed with greater ease by students at AHO. Typically within a studio environment (Killi & Morrison, 2015) students are led by a design brief that is attached to a specific context. The emphasis of the 'digital fabrication' elective course however, was to focus students' attention on specific exercises centred around AM tools, followed by a larger, open-ended design task (Ostuzzi, 2017).

Throughout the course semesters, the students were encouraged to develop their design projects using specific 3D printing processes and techniques, such as 3D scanning, SLS, FDM, SLS or SLA. The students presented each weekly project through a brief description, and their work was subsequently pasted onto boards assigned to each 3D printing technique. The boards hung inside the lab and acted as a database of experimentations which students could use for developing their project further. During the five-day workshop in which a single project had to be developed further, students could lean on their prior experiences, on experiences of others or create new ones.

Aside from providing imagery to areas of use and experimentation of AM technology, the involvement with student designers and architects provided me with the challenge of building an environment in which experiential learning with AM could be done. Rather than applying the tools in certain phases of a product development process, the programme was stressed as one which questioned phenomena of use regarding AM through product design techniques.

Whereas the involvement of student designs proved valuable in creating a learning programme for inquiry into AM technology, my own engagements build on particular aspects and pathways that were developed during the elective course. Apart from co-hosting the course semester, my engagements allowed me to actively participate in the same learning framework which was being developed.

In regards to the observations of design experts, they were primarily conducted to gain insights into developmental applications of AM in a real-world context. Complimented by a scope study of prototyping techniques (Capjon, 2004; Lim et al., 2008; Pei et al., 2011), the observations allowed me to obtain a qualitative, contextual view of the ways in which digital fabrication contributed to new ways of perceiving how craft knowledge contributes to developing AM.

In the next chapter I elaborate on the relationships between design practice and knowledge generation through and for AM. In doing so, it goes from an epistemological elaboration of design making and knowing, into an analytical model.

4 Design practice and knowledge for AM

Through the literature review in chapter 2, the focus on product design is oriented towards critical inquiry, which is carried out through the practice of research methods, as I recounted in chapter 3. In it, I outlined a methodology which is epistemologically concerned with providing multiple, qualitative ways of knowing about the uptake of AM, through a particular emphasis on a practice-based, *making* inquiry.

In this chapter I question the pathways and conceptual thinking that go into making *with* and *through* digital fabrication tools such as AM. Calling into attention constructionist and experiential frameworks for learning, I aim to arrive at a clearer link between aspects of making, analysis and critique. Specifically, I introduce the concept of *design-making critique* which emphasises product design methods as an approach to gaining deeper understandings of sociotechnical phenomena. The concepts and discussions introduced in this chapter form the foundation for which to develop critiques on AM technology, which is furthered in chapter 5.

4.1 Craft practice in digital design

In the following section I discuss links between craft and digital design, which helps me build up an argument on how craft practice facilitates the development of knowledge within a design activity. I specifically relate to the notion of craft as linked to bodily skill, imagination and the development of technical understanding (Sennett, 2008).

This attention to craft contrasts the apparent paradoxes in engaging with digital fabrication. While its history of use is closely linked to iteration and repeated use, tools such as 3D printers are perceived as linear processes between digital concept and physical presence. Its operation requires that a

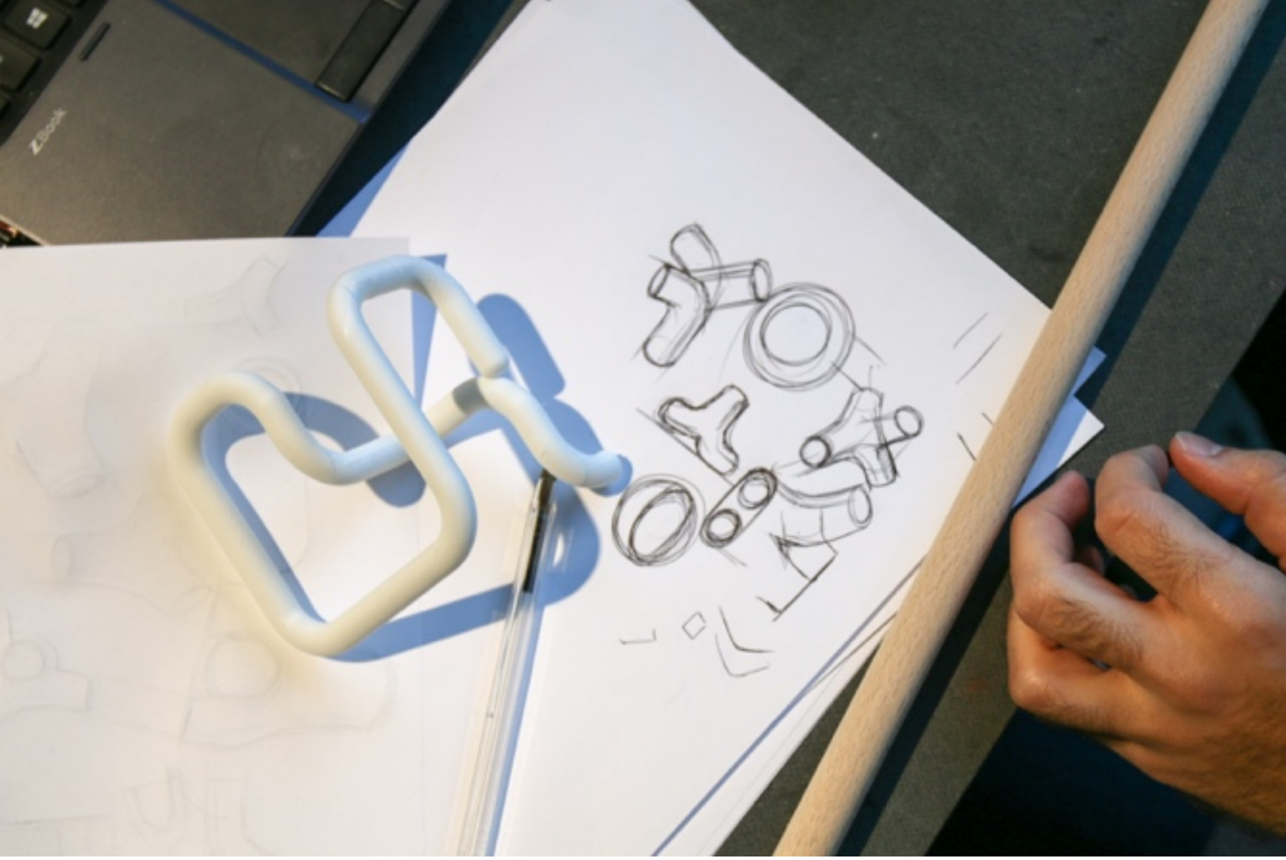

Figure 25 – Drawing, building and doing and redoing. Prototypes, sketches and material samples are but some of the materials that designers use to evaluate and refine their abstract ideas. Photo: William Kempton.

design is already present at the beginning of the process, ready to be turned into a physical presence. This paradox poses a clear challenge for the idea of a mutual, continuous engagement with the materials and tools that are involved. The *experiential* notion of craft as a form of thinking through the hand is still present, but it now has to be applied at the front-end of AM. The implication of this is a need for developing practices and pedagogies on design which are guided *through* AM. These pedagogies should cycle between formal and tacit understandings of the materials and the process.

As a part the *Research Through Design '15* conference, Christopher Frayling is featured in a series of video 'provocations' which put practice-based design onto the agenda of design research. In one particular video (Durrant & Price, 2015), Frayling takes up the topic of 3D printing where he argues the need to unpack craft knowledge through the process of design. Frayling reflects on the apparent conflict between the notion of craft as it was interpreted by William Morris as a process in-the-making, and the practices that go into making with 3D printing *before* it is fabricated by the tool. This conflict is perceived by the operation of 3D printers being predominantly done through CAD models, which are principally made through digital interfaces. Frayling (Durrant & Price, 2015), in regards to the many educational implications of 3D printing, states the following:

> The craft knowledge goes into the [CAD] drawing, so your understanding of materials, and the tactile, sort of knowledge that you have, and the experiential knowledge you have, all gets distilled into the drawing at the *beginning* of the process. You then plug it into this 'microwave', and there it does it, in resin … or clay, and so the design thinking comes at the front-end, when it used to come at the back-end. (02:44)

The core of Frayling's argument sets in relation the apparent conflict between the tacit, informal knowledge that is embedded in doing design, and the seemingly linear one-way process of fabricating artefacts with a 3D printer. He builds an image of the digital fabrication tool and its fabricated output as a static form, avoiding any mention of a situated understanding of either material or computational literacy. It appears as if Frayling views the idea of craft with digital tools as a rigid, one-way process. He thereby builds up onto the paradox between craft engagement and digital fabrication, which gives little space for contemplating links between the practices, techniques, and cyclic processes involved in digital fabrication.

Similar assumptions are also made by Kourteva and McMeel (2017) who discuss digital design and fabrication from the perspective of architectural practice. Their claim is that there is no 'digital design', and that it should rather be framed as 'digital fabrication' because it is a one-way, product-oriented process. Furthering this argument, they claim that the crafting of architecture remains largely realised through manual design techniques, such as sketching or cardboard model-making. This is due to the iterative, conceptual and easily discardable nature of such analogue design techniques. Their argument is founded on the notion of creativity as 'play', as it leads to moments of error, serendipity and improvisation. These valuable moments are, according to Kourteva and McMeel marginalised within contemporary approaches to digital craft, such as in coding and automation. It is this seeming disconnect between human playfulness and improvisation, and the rational logic of technique, which is valuable for my own argument on how design knowledge is made.

Frayling's (2015) and Kourteva and McMeel's (2017) discussions of digital fabrication present a dominant image of activities surrounding 3D printing as a one-way process. Frayling, in particular, compares the tool to a 'microwave', thus building on the idea that the 3D printer acts as a *black box* which simply churns out a precise fabricated shape based on exact digital blueprints. Neither does he provide basis for interpreting the many craft implications, or design specialist skills that are involved in the CAD drawing process, which has a significant role in digital crafts.

In all, I see the need to frame craft and digital fabrication better in terms of constructing new knowledge, as well as producing artefacts. I extend this to the repetitive and incremental nature of craft practice, which is described as a dialogue between concrete practices and thinking (Sennett, 2008). This dialogue acts as a form of evaluation which is applied both onto and through the mediums which are relevant to a practice, whether it be in digital fabrication or elsewhere. This notion of medium is likened to a piece of code by a computer programmer, or a set of prototypes by a group of student designers. The relevance of craftsmanship, as I perceive it, is as closely tied to developing satisfactory artefacts, as it is to develop knowledge around the subject of the practice. Satisfaction as Sennett recalls, is 'the desire to do a job well for its own sake' (2008, p. 10), So, in the context of craft, knowledge relates just as much to the technical character and behaviour of the medium, as it does to the imaginative techniques which are employed to the practice.

4.1.1 Digital craft knowledge

At the start of the chapter (Figure 25) I illustrate how a design scenario in with a student investigates 3D printed furniture joinery is aided by hand-drawn sketches, material samples and visual prototypes while digital CAD model is reworked. Rather than being a rigid, linear process, as Frayling, Kourteva and McMeel discuss, I argue there is a need to rethink the model in which technical knowledge of digital fabrication is complimented by both conceptual thinking and tactile experiences. This is where the notion of digital craft is useful to forward my argument – but how can it build on from perceived lack of feedback of digital design and digital fabrication? What role might digital tools have in relation to the aspect of knowledge construction in craft practice?

In order to argue that digital craftsmanship is a necessary for making knowledge through digital fabrication, it is necessary to unpack the apparent contradictions of craft as it enters digital space.

In the same wain, McCullough (1998) provides a detailed outline of how digital technologies provide new fields of interest for the digital-era craftsman. In his book *Abstracting Craft*, McCullough (1998) begins by exploring the foundations of handcraft from a human context (hands, eyes, tools) before reviewing the foundations of the computer as a *medium* (symbols, interfaces, constructions). Later in the book McCullough provides an elaboration of the core argument, that of digital work needing to be brought back to physical, human agency. By this, he means that the potentials of craft lie just as much in what we bring into it, as the technology itself. In doing so it provides a critical understanding of the way in which the digital medium, referred to by him as the computer, requires new sets of digital skills. The purpose of his discussion seems for the digital craftsman to be able to construct new mental working models.

In linking discussions of digital craft and fabrication to a model of product development, McCullough (1998) relates to how CAD creates a feedback loop between the design of geometries and the process models which guide product development. This loop, he claims, is 'superior to simply drawing up a design and tooling up production because manufacturing processes become more easily visualized and more quickly adaptable, and design becomes more easily executed as physical things' (McCullough, 1998, p. 52). From the text, it is possible to extract an underlying optimism in McCullough's (1998) claim towards human agency in the matter of making and designing with digital tools. As opposed to seeing these tools as mere improvements and optimised forms of pre-existing, hand-based craft tools, the advent of digital craft enables a new form of digital artisanry.

Taking on from McCullough's discussion of digital crafts it is relevant to discuss a series of problematics and conflicts relating to the application of craft within digital design. What comes out of this discussion is a concern for the practice of *doing* digital fabrication, specifically from within design practice. In addition, it is relevant to unpack the feedback loop which occurs *after* the process of digitally fabricating with AM, as I argue that this does not happen in a vacuum. As I explain further, the role of making representations in the form of material artefacts, prototypes, mock-ups and visual design representations plays a foundational role in concretising abstract design ideas. I therefore see it as relevant to discuss the conceptual thinking that goes into the process of engaging with AM technologies.

4.2 Constructive ways of knowing

Through the previous section I linked craft to the development of knowledge necessary to explore and imagine digital mediums such as AM. Specifically, it is through the feedback loop between making and knowing that an experiential learning is developed. Making in particular forms important to experiential learning, as it encompasses both practical and reflexive action which is founded in the technical engagement of tools and a device's material availabilities. The focus of this chapter is to elaborate on epistemological concerns regarding the nature of such an experience-based learning.

4.2.1 Constructionist views on learning

The concept of making, as it is brought up in contemporary subcultures such as the maker movement, springs out of a similar interest in practice-based engagement, which is vested in investigating emerging technological phenomena such as personal fabrication (Anderson, 2012; Gershenfeld, 2008). Arenas such as makerspaces and maker festivals take part in renewing this model of tinkering, hacking, self-repair and layperson design involvement. These arenas are linked to models of learning which tie closely which experience and embodied practice, such as *constructionist* learning. This form of learning differs from other instructionist pedagogies in that it moves from teacher-focused to experience-based learning. This amounts to an emphasis on the learner's engagement and expression through different media. These individual engagements are seen as the primary actions for the transformation of new knowledge, and in extension also the basis for knowing (Ackermann, 2004).

Pioneered by Seymour Papert (1991), constructionism sees engagement with different materials and mediums as fundamental. Latching onto learning experiences which are shaped through intermediary processes, constructionism provides an alternative pedagogy for subjects such as math and engineering. Through intermediary, or *transitional objects*, such as mechanical gears and computers, Papert (1991) observed how young children were able to build personal mental models in areas such as maths and physics. Notable examples of transitional objects also include the development of Lego Mindstorms, which allowed children to toy with advanced levels of computer programming (Papert, 1980).

Although trivially summarised as a 'learning-by-making', constructionism is a concept of learning which has epistemological similarities with other theories of learning. Of note are concepts such as Piaget's *constructivism* (Blikstein, 2013), in which Papert's (1991) constructionism brought its initial interest. Central concepts of constructionism involve learning as indirect, as it is always interpreted in the light of previous experiences. It also holds that the transmission of knowledge is not simply delivered, but is the process of experience. Last, it holds that successful learning theories should not ignore resistance (E. Ackermann, 2001).

4.2.2 Social constructivist / socio-cultural view on learning

While the constructionist emphasis on embodying experiences on theoretical concepts is relevant to my developing argument of making as knowing, its primary emphasis is related to the learning of maths, science and engineering subjects. The focus of this thesis however, is to develop a learning view which is not located within a single discipline or subject. Rather, it is interested in how practices and experiences with tools materialise (see section 2.3.4) new perspectives that are oriented on the social constructions of a technology. As such, I attach to a view which is situated closer to a constructivist ontology, which is actively engaged with accommodating and assimilating new knowledge from experience (Ackermann, 2001).

Other related approaches to this concept of learning include John Dewey's (1938) pragmatist and later social constructivist experiential learning theories, which are motivated by the 'organic connection between education and personal experience' (p. 25). In other words, Dewey's (1938) pragmatist philosophy of learning links real world objects that are not bound by the organisation of subject-matter. This focus on multiple subject-matters forms the premise for learning strategies such as the experiential learning cycle introduced by David Kolb (1984) (see section 2.5).

The model introduced by Kolb (1984) remains a key reference for any debate on experience and its influence on learning. His model sees reflection and action as two poles in a systemic learning process, which also resembles discussions forwarded by Donald Schön (1983). Schön (1983), who focuses his attention on professional development, also takes up this very dialectic – between what is being *done*, and the reflective process that is carried through its actions. The concept of reflection-in-action, which is central to Schön (1983), occurs when the practitioner looks at past events to inform how to make decisions in the present. The core of Kolb's (1984) framework, however, is the centrality of the lived experience. The cyclic schematic also emphasises this continuity, which is evidently more enclosed compared to Schön's (1983) broader concept.

Kolb's (1984) pedagogical model is organised around four distinct modes of experience: *Concrete Experience, Reflective Observation, Abstract Conceptualisation* and *Active Experimentation.* Building on this model, I later set it into relation to my own designerly informed model of learning. I also introduce a critique of Kolb's (1984) experiential learning, as it gives little instruction about what is being learned, which is a fundamental part of the critical approach I am setting up in this thesis.

4.2.3 Re-learning, design and AM

The purpose of introducing theories on experiential learning into my discussion of digital craft, is to connect a view on how learning is made on a subject, with that of knowing through acts of design. As I observed through my review of the Italian design radicals (see section 2.1.3), the project of re-learning and re-interpreting such as in the Global Tools workshop, was considered necessary by its participants to observe on the oblique links between use, technology and design. The interest that these workshops took in engaging with craft techniques and artefactual production was not oriented on debates of craft vs. industrial production. Rather, they were initiated from the perspective of re-schooling, specifically in relation to how learning was drawn from crafting experiences (Borgonuovo & Francheschini, 2015).

It is through this process of re-learning-through-making that constructivism forms a useful part of my theoretical framework. Moreover, this process of re-learning through making is particularly relevant as a form of developing knowledge on emerging technologies, such as those of interest in this study. Emerging technologies such as AM are in fact subject to a vast amount of speculation. However, this speculation is often built on biased assumptions of what the technological capacities are, as I review in my literature review of claims to AM technology.

The idea of introducing experiential learning to the topic of emerging technology and interpretation, is to facilitate an unpacking through design practice which is subjectively and critically approached. In other words, I see this embodied, critical practice as relevant to building visions, anticipations and interpretations of AM use. In the next section, I make links between learning, design and prototyping into a wider view on new product development.

4.3 Towards design learning

Leading up to this chapter I have discussed the how the knowledge development on digital fabrication technologies such as AM can be attained through craft practice. This craft practice is characterised as one which attains knowledge through the active and reflective practice of making (Schön, 1983), which is closely linked to experiential learning (Kolb, 1984).

In this section I turn towards NPD as a strategy for developing situated knowledge, which is facilitated through the making of prototypes. The experiential learning model introduced in this section, the Additive

Experiential Learning Cycle (AELC), is specifically developed as a learning view for AM. It is based on research data developed in the previous chapter, and builds on from established practices with 3D printing tools, such as RP and Critical Making (Ratto & Ree, 2012).

The connection between AM and NPD is particularly relevant, as I recounted in the introduction (see section 1.2.2). Under the banner of RP, 3D printing tools provided designers and engineers with the capacity to augment features and geometries that were constructed through CAD. While the high costs of the RP process initially restricted its use to the latter stages of an NPD process, restrictions are now being lifted as access to digital fabrication techniques eases, bringing into question how it might facilitate new approaches and guide the development of new design practice and learning.

4.3.1 Prototyping as developmental design learning

In the following section I will discuss how uses of prototypes and multitypes (Capjon, 2004) are integral to my experiential learning view on design. I will unpack these artefacts' relations to my holistic framing of NPD and AM, which I will draw together later in this chapter.

The practice of design is a combination of approaches that are richly recounted through implementing methods (Kumar, 2012), ways of thinking (Lawson, 2006) and richly illustrated narratives (Milton & Rodgers, 2013). A common sight among prospective and practicing designers is their involvement with making models and prototypes in various shapes and forms. For a designer working with screen-based interactions, a prototype may take the form of a simple wireframe sketch or an animated representation of a particular gesture. For a service designer investigating new means of shared transportation, extensive visualisations or gigamaps of hidden relations between seemingly unrelated categories may be an appropriate means of prototyping (Sevaldson, 2011). In product design, the use of representative forms, made in cardboard, clay or low-density foam may provide useful in terms of reviewing a particular aesthetic or as an experience prototype (Milton & Rodgers, 2013, p. 101).

In all, a developmental view of prototyping can be seen as a filter through which an abstract design idea is created, communicated and refined. Some view prototypes as a 'vessel for traversing a design space' (Lim et al., 2008), while others view prototypes as experiential components for a design to be understood, explored and communicated (Buchenau & Suri, 2000). In Figure 26 I illustrate my view on prototypes as filters which enable design

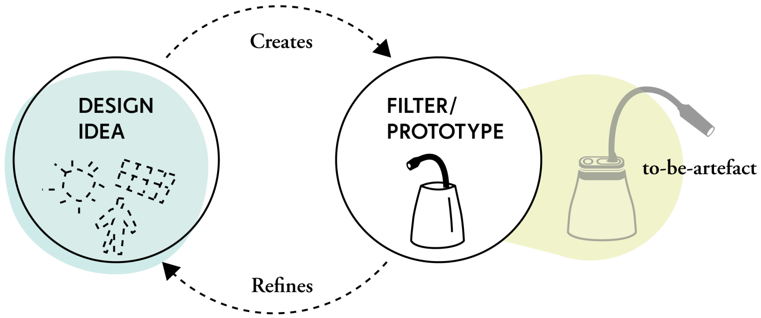

Figure 26 – Prototypes act as filters or manifestations of a design idea. Illustration: William Kempton (2017b).

ideas to be created and refined. The notion of filtering, as proposed by Lim et al. (2008) is used as a metaphor for explaining the incompleteness of prototypes. The notion of filter is just as much meant to isolate wanted as well as unwanted aspects a design process. The actions which facilitate this process, illustrated in Figure 26 as *creates* and *refines,* are used to emphasise the flexible and layered nature of the prototyping process. As opposed to being problem-solving, the idea of prototyping may be framed as problem seeking, or even problem defining.

Prototyping practices seldom happen in a vacuum because the purpose of making prototypes is often tied to specific objectives, as a means of articulation, communication or as an embodiment of a particular function. Whereas the prohibitive availability and cost of previous generation RP techniques associated its use with the decisive stages within a product development cycle, low-cost and consumer-oriented digital fabrication tools such as desktop 3D printers opened it up to newfound uses within a developmental design practice. Let me connect this fuller with reference to the research published as part of this doctoral study.

In my third publication contained within this exegesis, titled 'The Impact of Making', I examined the emerging role of 3D printing and AM within design prototyping (Figure 27). Contextualised through a series of cases, I attempted to situate some of the uses and ways in which AM prototypes are involved within expert design processes. The first case followed the development of the Durr wristwatch, made by the design collaborative Skrekkøgle. Referring to the shivering sensation the watch gives every five minutes, the Durr watch was developed and sold in a series of staged or stepped versions. The initial version, named Durr Alpha, was released in a

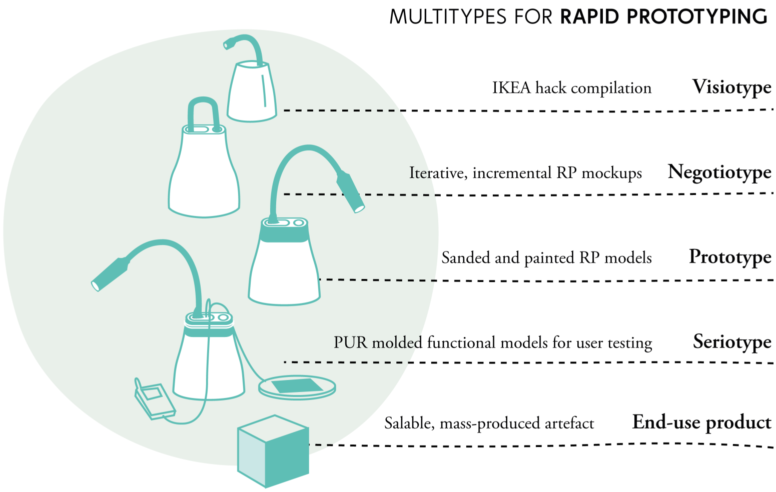

Figure 27 – Multitypes in RP, explained through various models in the development of the SunBell lamp. Illustration: William Kempton (2017b).

limited, completely hand-assembled edition, featuring an entirely AM fabricated housing. Having experienced the intricate process of logistics and quality-control, Skrekkøgle realised the possibility of making another, improved iteration of their watch. The following year Durr Beta was released, incorporating a milled aluminium casing and a custom PCB. This time, the use of AM was reduced to the inner housing.

The second case involved a utilitarian lamp, called SunBell, which was analysed through the different artefacts that were made throughout its development process. The project, initiated by the Norwegian design agency K8, was intended for off-grid use by roughly a billion people in developing countries who currently rely on hazardous kerosene lamps as a main source of artificial lighting. The lamp incorporated a small, solar panel for recharging an integrated battery, which also functioned as an off-grid mobile phone charger.

As a way of analysing and relating the multitude of prototypes and their particular roles, I built on Capjon's (2004) framework for relating prototyping to specific stages of an NPD cycle. The framework, further contextualised in research on AM and product design by Killi (2013), is set in relation to a series of *multitypes,* with its respective role in the NPD cycle. As seen in Figure 27, these *types* are described as *visiotypes* (initial mock-ups

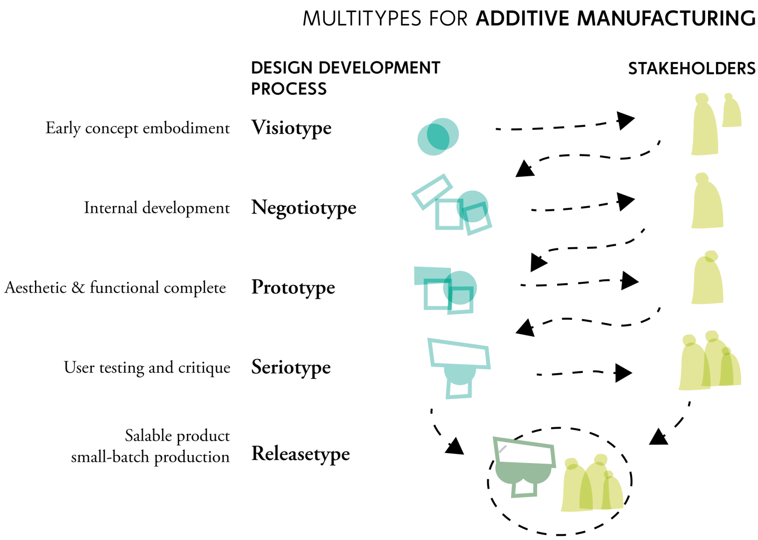

Figure 28 – Multitypes for AM. Illustration: William Kempton (2017b).

at the fuzzy front end of a design project), *negotiotypes* (conceptual, communicative models developed with internal actors for materialising mental imagery), *prototypes* (evaluative concepts for external actors) and *seriotypes* (functionally complete, facilitative models for generating external user feedback). Last, the developmental cycle is seen as culminating in a saleable, mass-produced artefact. In the case of the SunBell lamp, this was a product consisting of various injection moulded plastics (ABS and PC), in addition to the necessary electronic components, such as a PCB and a LiFePo battery.

The case study, which discussed multityping activities within an RP context, provided a starting point for the next point of discussion concerning the role of AM, as its multitypes extended into an end-use context. Culminating this discussion, I introduced the concept of *releasetype* as a

> digital/physical hybrid artefact consisting of a design framework and a user interface. As opposed to conventional product design where a typical design task is the shaping of a single artefact, the new design task becomes the forming of the releasetype solution space and interface. The releasetype is still the result of a systematic design development, incrementally matured through stages of visiotyping, negotiotyping, prototyping, and seriotyping. However, as a

> digital/physical product hybrid, the releasetype is tangible to its users primarily through an interface, where it can be extracted and fixed into physical space. (Kempton, 2017b, p. 136)

The introduction of the term releasetype was foremost an attempt to elaborate on a vocabulary for developmental prototypes within an NPD process whose output is primarily driven through AM. Driven by the question of how expert uses of digital fabrication provides new models for product conceptualisation, the naming of the term *releasetyping* (Figure 28) was also done to draw attention to new models of user-designer collaboration. This, I regarded, would be an important criterion for the successful use of AM for consumer-oriented products.

4.3.2 An Additive Experiential Learning Cycle

However, as I elaborate my discussion towards design practice as it passes into consumer-oriented focus, I refer back to a discussion of experiential learning and prototyping as an approach to design. Specifically, I relate this to an approach to learning which is facilitated *with* and *through* AM. This is a discussion which was the topic of the fourth publication of the PhD study, titled 'Meeting Learning Challenges in Product Design Education with and through Additive Manufacturing' (Kempton et al., 2017).

Coming out of a textual description of a series of workshops and courses which were developed and run at AHO, I created the AELC model (Figure 29) based on our approach to design learning and AM. The model is meant to reflect the dynamic nature of digital fabrication and builds on a structure which resembles that of Kolb's (1984) experiential learning cycle. This cyclic and non-linear approach to learning with digital fabrication can be described as one which is invested with production-based knowledge on potentials that are made possible through the malleable and flexible characteristics of digital fabrication. The model orients AM between socially and technically oriented conceptualisations of design. These conceptualisations are represented by critical making (Ratto, 2011), which follows a constructionist design inquiry, and RP, which brings technical relevance to a design practice. The experiential learning cycle is made up of four distinct instances, and together they comprise my particular learning view on AM. This is a view which blends distinct approaches to design through its incremental and experiential progression. This progression is represented by four instances which follows Kolb's (1984) model, and consists of *active experimentation, concrete experience, reflective observation* and *abstract conceptualisation.*

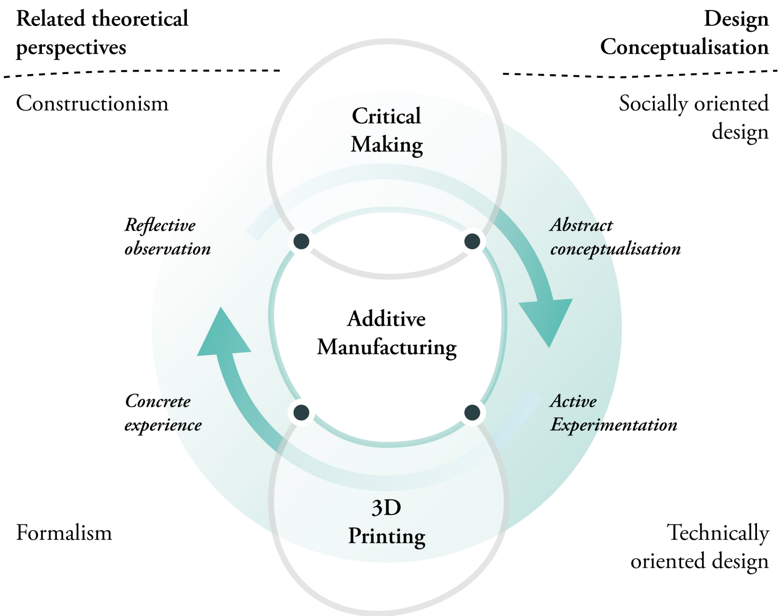

Figure 29 – The AELC model describes the relation between critical making, AM and 3D printing in relation to design conceptualisation and related theoretical perspectives. Illustration: William Kempton (Kempton et. al., 2017).

The first two instances, active experimentation and concrete experience, comprises the technically oriented design which is represented by RP. These instances can be seen as activities similar to those in an NPD process where prototypes and multitypes are assembled and employed. In relation to the case mentioned in the previous section on the Sunbell lamp, these activities include the making of crude, low-definition visiotypes, to aesthetically refined, sanded and painted prototypes (Figure 27). The role of RP within the experimental learning cycle therefore represents the technical activities which lead up to, and include ways of displaying, communicating and evaluating formal functionalities.

At the other end of the experiential cycle I refer to critical making. It comprises the two latter instances of the experiential learning cycle, which are reflective observation and abstract conceptualisation. Critical making, as described by Ratto (2011), forms an important conceptual framing for the learning cycle, as it brings into it a critical and reflective assessment. Whereas RP is concerned with the concrete experience of engaging with AM's materials, critical making is concerned with seeing how these concrete experiences act as 'reflexive prompts' (Resch et al., 2018). As such it is oriented toward a social aspect of a design process, where broader cultural values surrounding the particular technology are assessed. So, in contrast to RP's concern for technical expertise which is found at a micro-level between tools and immediate users, critical making perceives the RP experience and experimentation in relation to actors and a context at a macro-level.

Rather than being independent of each other, the two approaches (RP & critical making) are complimentary to the development of my own learning perspectives on AM. However, the contrast between the approaches in scope and character appear challenging for a holistic development. Moreover, the fact that it sits within an enclosed loop (Figure 29) makes it appear as if both RP and critical making need to be involved for any full transformation of knowledge to be attained. As such it is necessary to reflect on the very experiential learning model itself.

Since Kolb's initial study in 1984, many criticisms of his experiential learning cycle have been voiced (Greenaway, 2002). One of the critiques forwarded by Miriam Webb (2003) brings attention to the four-stage cycle, and questions whether the cycles are distinct and necessary to complete for any learning to take place. Webb's (2003) position is that it is not essential, and further contends that both modes of concrete experiencing and abstract conceptualisation require a *full* transformation of experience. In other words, the abstraction of experiential learning into a loop model is misleading. Rather, the distinct waypoints can be considered to be interwoven and contextually dependent.

Seen in this light, Kolb's (1984) cycle superimposed onto the model in Figure 29 must be considered a preliminary framework from which my own critical design framework departs. In order to elaborate on this further, I will introduce the concept of *design-making critique* which weaves together the formal characteristics of RP with the constructive and interpretive emphasis of critical making. It does so in order to orient experiential learning towards an unpacking of emergent technology such as AM.

4.4 An experiential design approach for making critique

Having now discussed the relations between craft, technical expertise and reflective thinking as an experiential process of knowing about AM, it is important to bring the discussion back onto design. For it is a perspective on design as new knowing-via-making new that I am arguing for.

This conception of design depends on the experiential joining up of approaches such as RP and critical making. Yet the application of critical making activities into a design context proves a continuous challenge, as the idea of materialising reflexive and abstract prompts can be seen as overwhelming for a prospective design practitioner. It is therefore relevant to consider – how can critical making be made more relevant for a designerly inquiry which is interested in giving shape and expression to its investigation of emergent technologies such as AM.

4.4.1 Beyond critical making

Referring back to Ratto (2011) and his discussions related to critical making, it appears that little help is given to aid designers with engaging and operationalising critical making. Ratto (2011) places great emphasis on explaining how critical making can prove a useful methodology to understand problems of an abstract, humanistic sort, while at the same time leaving behind the crowd from where his methods spring. This is not to say his notion of *making* abstract concepts is irrelevant, but I argue it must be better understood from within design. What comes out of this argument is the contention that there is a need for overlaying frameworks in which designers can see their engagements from the perspective of technological critique. One way of doing this is to facilitate it through an experiential learning cycle, in which one moves in and out of formal and constructive modes of engagement. This has been the work of the AELC model, which I introduced in the previous section (see section 4.3.2).

But in moving beyond the circular layout of Kolb's experiential learning cycle, which can be critiqued as adhering too rigidity to each successive stage of learning, I wonder – what might an overlaying framework look like? And how may it be visualised in such a way that it runs the socially and technically oriented design conceptualisations in parallel, rather than successive? In the following section, I close in on new concepts for accessing reflective critique within a design-driven process.

4.4.2 Design-making critique

Critical making is foremost described as a material practice in articulating theories and abstract notions of technique and social relations (Ratto, 2011). While prototyping has a particular function in this articulation process, it is only seen as a means of extending new models and theories. The way in which making is performed and described by Ratto (2011) is also heavily influenced by computational materials, such as Arduino prototyping boards, sensors and coding.

Building on critical making as a critical approach to exploring sociotechnical issues, I will explain the concept of *design-making critique* in more detail. The purpose of this concept is to frame design in such a way that is joins critical, technological reflection into the process of developing new artefacts. It does so primarily through means of making, which are used to evaluate both the formal, as well as social characteristics of technology. Specifically, design-making critique relates to a context in which usable prototypes are at the forefront of discussion. As with critical making, design-making critique brings on concepts such as *non-determinism* (Feenberg & Callon, 2010; Winner, 1997), *materiality* (Leonardi, 2012; Suchman, 2007) and *inscription* (Akrich, 1992; Law, 1992) from sociotechnical studies, which guide how design conceptualisation is performed.

Design-making critique is composed of three key words. *Design,* which relates to the activity of shaping artefacts to an environment, is joined in with *making* to emphasise the activity that goes into such a shaping process. Here, making refers to Ingold's (2013) notion of making as *knowing from the inside.* The emphasis on making as an activity central to design is to position its function through which reflective thinking is done. Lastly, *critique* stands to represent the reflective practice that is implicit in the design-making approach. This reflective practice is emphasised through the practical engagement with materials and tools, and reflection on the techniques, goals and contexts the practice is engaged in.

As with the AELC model (Figure 29), design-making critique transitions between a socially oriented design, which emphasises a constructionist approach, and a technically oriented design, which emphasises the characteristics of technical objects, such as 3D printing tools. I see these different conceptualisations as representing complimentary modes of the approach, which I argue bring into relevance both social and technical agency. On the one hand, there are certain qualities and characteristics that are inherent in a technical object, while on the other hand, these characteristics are subject to interpretation and subjectivity. As an example, the freeform fabrication process of a 3D printer, combined with the parametric ability of CAD makes it possible to fabricate objects that are unique and that can be tailored to fit a certain user or group. Famous examples of this includes hearing-aids that are moulded to fit specific users (Masters, 2002), or dental alignment braces. However, as seen with AM entering other healthcare domains (Gibson & Srinath, 2015), this tailoring could pose numerous challenges from an adopter's perspective. How could the adopter engage with, or even modify the design-to-be such as a medical implant, before it is implemented? What prior experiences does this adopter have which allows it to modify a design-to-be in accordance with the designer? And even further, how can the designer know how the ability to modify a design benefits the adopter? In other words, the belief that the designer can assign purpose and use to a technical device brings attention back to theoretical notions from technology studies, such as determinism in technology (see section 2.3.2). This determinism hinges on the belief that a design can be can be fully resolved by the designer as it is placed in a context (Ihde, 2008), which I argue against. In short, technological determinism is a belief that design-making critique attempts to work against, through its constructive and iterative approach to learning about the materials, tools and processes of making with technologies such as AM.

To transition between the technically and socially oriented modes of design conceptualisation, design-making critique relies on an experiential, iterative approach in which prototypes and mock-ups are made to evaluate aspects of a product design. This includes an attention to the aesthetics, functions and usability of a product. However, design-making critique must also pay attention to the way in which these processes are performed. What kind of design tools and techniques are used to conceptualise and make them? Where are these concepts situated? What is the purpose of making such concepts? While all these considerations might indirectly relate to each other, they are arguably subject to a process of experience.

The learning cycle in Figure 29 is the experiential model which the design-making critique approach builds on from. However, it differs in that full transformation is not required to acquire knowledge. As such, the concept of design-making critique is best described as an experiential cycle, but as one which stresses that transformation of experience does not arrive at the same point from which it departed.

4.4.3 Outlining design-making critique

The illustration in Figure 30 visualises such a model. It should be read as a three-dimensional model, with three interrelated aspects making up the dynamics of design-making critique. These aspects are defined as (a) *design conceptualisation,* (b) *making in context,* and (c) *experiential learning.* Design conceptualisation (a) is represented by a double helix, where each helix corresponds to a social or technically oriented conceptualisation of design.

In technical orientations of design, focus is centred between the proximate designer and its active engagement with AM’s technical processes. The emphasis on *proximate* recalls the closeness between the designer and the technical characteristics of a 3D printer. From this view, the technical

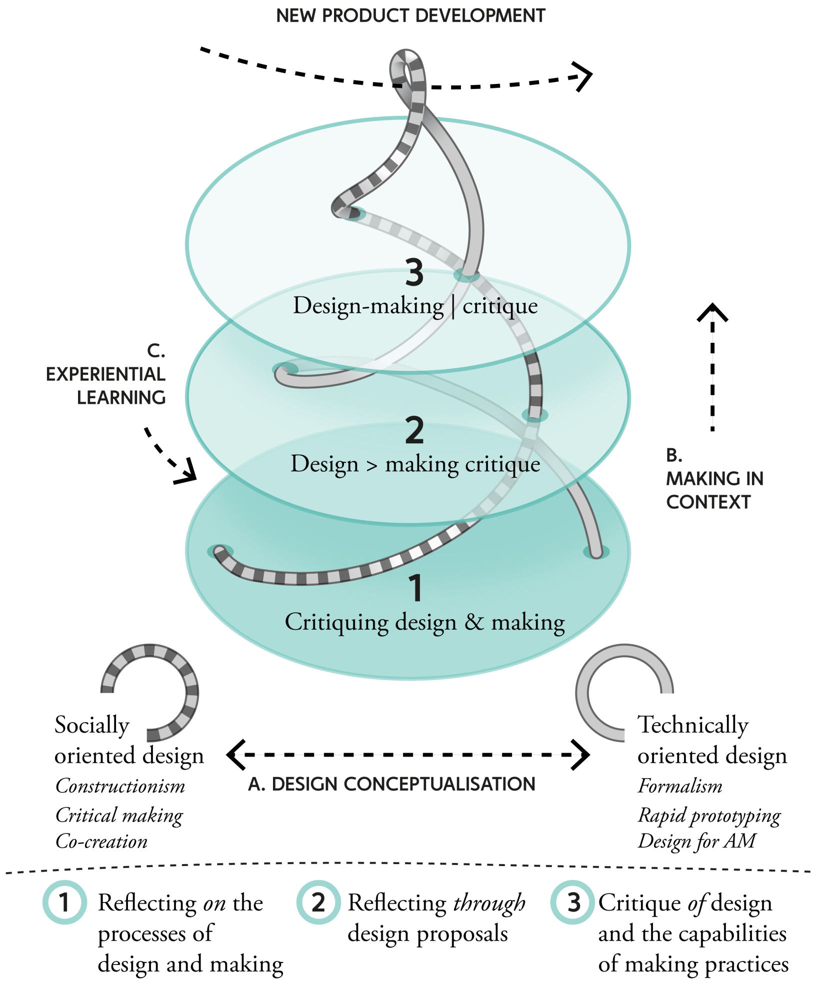

Figure 30 – A model of Design-making critique. The concept can be applied in different ways – in reflecting on a particular design process, as a way to create alternative designs and from a critique of how design and making negotiates with sociotechnical issues. Illustration: William Kempton.

characteristics of a 3D printer may be assigned to established technical capabilities, such as customisability, enhancement, computation or volume (Conner et al., 2014; Killi, 2013, p. 28). In RP, these capabilities are used by the proximate designers to achieve certain aesthetic or functional qualities of a design. In AM such characteristics, or affordances, can be seen as having a large influence on how manufactured goods can be made through AM (Doubrovski, 2016).

In contrast, social orientations of design understand the technical characteristics of AM in relation to a contextual use. From this contextual perspective, the technical characteristics of AM are always applied onto existing practices, and is therefore subjected to potential conflicts of interest. For example, the process of adapting prosthetics to individual users is predominantly done through manual labour. Rather than seeing 3D printing as a technology for challenging this existing expertise, research projects such as 3D PrintAbility (Resch et al., 2018) have sought to develop technologies that serve and complement the existing, labour-intensive practice of making prosthetics. Through co-creative collaboration between designers and clinical expertise, projects such as 3D PrintAbility have sought to discuss how 3D printed artefacts may act as “objects for discussion and reflexive prompts, rather than functional prototypes” (Resch et al., 2018, p. 116).

The point of separating these design conceptualisations is to make a clear distinction between constructionism (socially oriented) and formalism (technically oriented) as relevant theoretical perspectives on design. A constructionist perspective interprets technical character as a quality to be revealed. For example, a designer might find that PLA plastic adheres well to nylon stockings. Given that many desktop FDM 3D printers have exposed fabrication beds, the designer might attach the nylon fabric to the fabrication bed. Material samples and patterns could be made, with the designer imagining uses or purposes as the project develops. The design, in this case a nylon stocking with PLA plastic texture, is an embodiment of a new materiality, and source for new meaning. However, a formal perspective might apply rigour to the experiment, as it perceives AM primarily from its technical qualities, and translates them logically according to the task at hand.

The relation between formal and constructive design conceptualisations can also be seen in reverse, in that one conceptualisation compliments the other. So, in the above-mentioned example, a technically-oriented (formal) design can be seen as the foundation for which a socially-oriented (constructive) design activity is enabled.

Rather than making rigid distinctions between these design conceptualisations, the aim of the model is to see them as complimentary. In order to do so, the model introduces the aspect of making in context (b) which is distinguished by three separate stages. Importantly, this aspect is facilitated through the practice of making, which I have now established as a form of knowledge activity. This form of knowledge activity, as I have also established, is necessarily an experiential one, as the model (aspect c in Figure 30) conveys. It involves concrete experiences and reflection on the experiences in order to move between the stages of the model. These stages are: (1) reflection *on* the making process, (2) reflection *through* design proposals, and (3) critique *of* design and the capabilities of making practices. Together, model can be seen as an approach to a new product development process.

At a preliminary stage, design-making critique emphasises the methods and activities which are made. The designer might consider questions such as – What purpose could a particular user-survey or fieldwork give to the project? How can product semantics be explored through the making of mock-ups? What materials could these mock-ups be made of in order to be tested out in a suitable environment?

Forming questions around activities and application of methods requires the designer to reflect on how to articulate the aesthetic, or technically functional aspects of a design. It might apply to the development of novel products and place attention on the way in which a design could be perceived, and how it may be subject to misuse. Relevant questions about the design could include the following: What aesthetic, functional or social functions does the product device perform? What are the symbolic qualities of these particular use functions? In which ways could these functions be non-intentionally used?

Whereas the primary stage reflects on the proximate and internal dynamics of a design-making process, the secondary stage of design-making critique applies to design as a practice through which the critique is being made. At this stage, attention is given to strategies for making plausible future visions, and on extrapolating alternative scenarios for emerging technologies through design (Auger, 2013). To date, this attention to proposing alternative designs is taken up in areas as Critical Design and Speculative Design (Dunne & Raby, 2013), where design proposals might take a certain cultural position, more than being a methodical approach. Design-making critique, as a form of critical inquiry, is not solely engaged with making alternative designs. Rather, it is understood as an embodied form of the primary-stage design-making critique, as it brings room for reflection through its design. In other words, it problematises areas of conflict revealed in the first stage, and articulates it through a practiced approach.

The designer might then ask the following relevant questions: How may quirks, tendencies and unintended uses of a particular design or technical device be articulated through its form, or way of use? Through which means could the design project be communicated to be understood in the context of which it is intended to exist?

At the third stage, design-making critique applies to a critique *of* design and making practices and it shifts the emphasis to reflect on the development process itself. How does a situated view of speculative artefacts deepen our conceptual understanding of technical characteristics or human intensions? On this level, it is relevant to consider the underlying goals, the application of design methods and the context in which a design project and its artefacts are made. To arrive at a clearer articulation of this concept, later in this study (see section 5.2.1) I introduce ways in which analyses can be made through the emergent uses of AM technology.

Lastly, in the next chapter I facilitate a critique regarding the development of technologies such as AM. Using critical theories of technology (Feenberg & Callon, 2010; Ihde, 2008), I set these discussions in relation to an argument which sees situated use as relevant to its development. I introduce the concept of *emergent use groups* as the specific, subjective contexts of use which contribute to developing interpretations of AM. As previously discussed, the focus on uses as opposed to users is important for my own analysis (see section 1.4.1).

Whereas relevant social users and stakeholders provide ways of understanding the historical underpinnings that pave the way for a contemporary understanding of a given technology, I claim that the emergent uses provide insights into future-oriented contexts of AM. I then explain how these uses may be sampled and located from *within* design practice. The aim of the resultant framework is to enable the designer to obtain a clearer relation between practice and its relation to technological critique.

5 Developing a critique of Additive Manufacturing

This study has established a critical perspective on the sociotechnical development of AM that is given particular emphasis in my critical review of AM in Chapter 2. Using the concept of utopia and dystopia, I attempted to locate discussions on AM that are found in relevant literature. The reason for categorising the review according to these positive or negative visions was to pinpoint reductionist views on AM's technological development. This is arguably a view in which political, social and cultural phenomena are not taken fully into account (Winner, 1997). In doing so, I drew attention to a non-deterministic view on technology, which emphasises the influence of tradition and cultural practice and informs how design, and by extension technology, is developed (Feng & Feenberg, 2008).

Applied to the context of design, this discussion of technological non-/determinism provides a theoretical positioning to the discussion of agency within design practice and research. I link my views on *non-determinism* with those found among theories located within the STS domain (Jasanoff, 2012) whose attention to a nuanced view of sociotechnical development is relevant for this study. Specifically, I link my views to constructivist analyses which emphasise and interpret the various power relations between social stakeholders and technological systems (Ihde, 2008; Leonardi, 2012; Orlikowski & Scott, 2008). Of note is Feenberg's (2010) critical theory of technology, which springs out of the framework of (social) constructivism. Feenberg (2010) talks about technology as mediated through cultural heritage and tradition, and its adoption of 'neutral' technological devices as 'interaction between reason and experience' (2010, p. xviii).

In deterministic accounts of technology, analytical perspectives are often seen as taking a macro-level analysis, as opposed to a meso- (Misa, 1988) or micro-level analysis. In a macro view, dominant power-structures are seen as the cause of historical change. A micro analysis appears in Bijker's (1997)

Figure 31 – A mobile robot transporting trays of 3D printed components at Ford's recent Advanced Manufacturing Centre in Glendale, MI. The $45-million centre, which is seen in this caption in a promotional video, is advertised by Ford as the 'reinventing' the assembly line, which is significant to Ford's manufacturing heritage (Ford Motor Company, 2018). Photo: Ford Motor Company.

socio-technological analysis which emphasises the uses and interpretations of various social groups and their importance in the development of emerging technologies. Critical theory of technology, however, emphasises the influences of tradition and the cultural practices that inform a design (Feng & Feenberg, 2008). In other words, this theory, through concepts such as instrumentalisation theory, allows conditions, practices and locations of a design, (be they physical or a service), to be understood differently across diverse environments.

Feenberg (2008, p. 112) illustrates how everyday cultural practices inform design in his example of the North American roads and the Dutch roads. Here, he discusses how the former, having been dominated by cars through the politics of urban planning, created an image of the road as a place for cars, while the Dutch roads continue to be synonymous with both bicycles and cars (Feenberg, 2008).

Further, in relation to models of innovation the manufacturing sector, it could be argued that entrepreneurship and start-up policies from the IT sector and its emphasis on 'innovate here/produce there' is harmful. This is primarily because of the longer time-perspectives manufacturing-based innovations require (Bonvillian & Singer, 2018). Figure 31 shows Ford's Advanced Manufacturing Centre in Glendale, MI, USA. In the image, a mobile robot can be seen transporting trays of 3D printed components. Meanwhile, a group of individuals can be seen in the background, talking to each other. The image recalls a renewed attention to hardware-based innovation as *Advanced Manufacturing* technology is accessed (Bonvillian & Singer, 2018). Considering Ford's historical influence on mass-manufacture and assembly, one may wonder how Advanced Manufacturing may provide alternative models for entrepreneurship and growth beyond an 'assembly-line approach' and whether this image replicates legacies or offers new product/practice relationships.

5.1 Emergent uses and technological design frames

Emphasising how background conditions forms the perception of purpose and function, is valuable for understanding how technologies continue to develop. As such, these conditions are argued as relevant for analysing how developments in AM occur. In my review of critical theories of technology (see section 2.3), I mentioned that technological determinism as a view gives little emphasis to social agency. I then discussed social agency in relation to emergent technology, which led to the introduction of theories such as inscription and materialisation, and how they take both technical and social agencies into account. This sociotechnical emphasis provides a useful position to this study, because it provides a framework through which to interpret developments in technology from a design perspective. This design perspective gives a nuanced view to the forces at play in the emergence of AM.

In my assessment of AM technology and emergence, design practice is arguably important in negotiating the space between that of technical feasibility and social understanding. To make this analytical move, I talk about the practice of design, and specifically that of product design, as a practice which is engaged with understanding theoretical concepts and issues through modes of observing, conceptualising, making and re-making. While such methods may be equally relevant for a marked-driven design practice, my intention is to position them towards an anticipative, RtD practice (Stappers & Giaccardi, 2017).

5.1.1 Tracing contemporary AM uses

Discussions on AM are found on both micro and macro scales, from individual applications of technology, to systemic changes to the production of goods. However, many of these analyses are inherently biased because

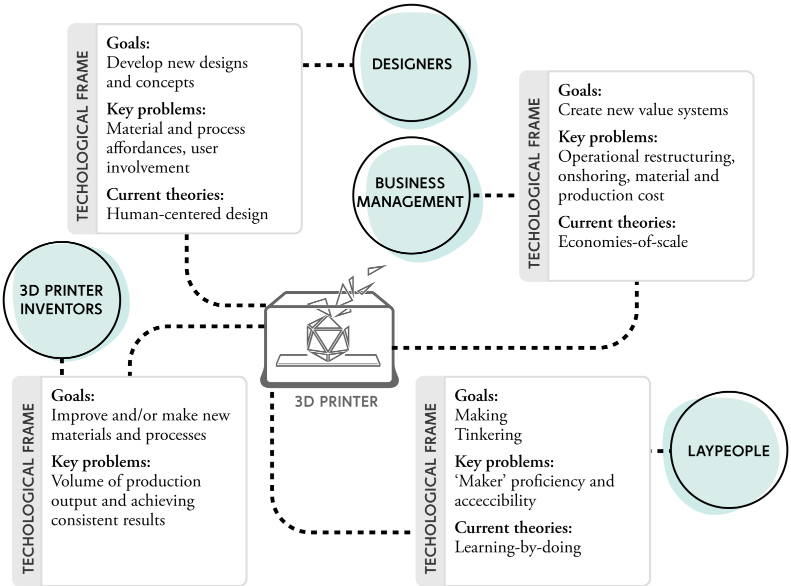

Figure 32 – The relevant social groups relate to a technological artefact through a technological frame. Illustration: William Kempton (2017a).

they fail to form analyses from both ends of the scale, thereby entangling themselves in positive, negative, utopian or dystopian visions. As discussed above in sections 2.4 and 5, such utopian and dystopian visions might also be the result of technological determinism at play.

To facilitate a designerly analysis of AM development, I position my discussion between a macro view, in which technical capacities must be abstracted and conceptualized, and a micro view, in which subjective use and interpretation may vary. As such, I recall Misa's (1988) attention to a meso-level analysis. This is a view in which different use and interpretations are made apparent through revealing connections between a micro- and macro-level. The need for this mid-level analysis is to illuminate the intersection between broad technical influence and subjective uses.

In the second publication contained within this thesis, titled 'A Design Sociotechnical Making of 3D Printing', I attempt to identify different design views on AM through a study of the social constructions which together allow me to discuss and recollect a contemporary view on AM. This view was formed through analyses of different stakeholders and *relevant social actors*. This method builds on Bijker's (1997) framework for analysing the social constructions of technological development. In my analysis, I identified these actors as *designers, business management, 3D printer innovators* and *laypeople* (Figure 32). The reason for using such a relatively wide scope of actors, was to make an account of the different uses and discussions surrounding AM. These are discussions which vary widely, and range from the current designers' uses of AM, as being oriented towards RP and new product development strategies, to a political discussion of AM. This is a discussion which draws closer to economic theory such as economies-of-one, and the on-shoring of goods manufacture (see Figure 32).

The relevant social groups selected for the study on AM were chosen from top-level actors, as my point of discussion was to unpack the design capabilities that were introduced among its relevant users. Through a common *technological frame,* consisting of characteristics such as end-goals, key problems and current theories, it was possible to unpack and develop an analysis based on their diverse and disciplinary standpoints.

It could be argued that such an analysis orients too heavily towards the social forces which make up a view on AM. As Bijker (1997) argues, 'Technological development should be viewed as a social process, not an autonomous occurrence. In other words, relevant social groups will be the carriers of that process' (p. 48). The point of discussion here is not to draw on either-or arguments. Rather, it is to introduce theories for analysing social factors to AM, which I argue is broadly dominated by technical research.

5.1.2 Tracing emergent use groups

The process of identifying relevant social groups can be carried out through various forms of sampling. Social groups may be sampled through *snowball sampling,* where acquaintances are sampled at the end of a dialogue with existing research subjects, or through a survey of relevant literature. In the study conducted in publication 2, the relevant users such as *laypeople* and *3D printer inventors* were identified through a scope review of the literature which discussed design in the context of AM. Aside from being a general selection of users (one could argue that laypeople could be arranged into many different sub-groups), they were also identified as *relevant* to my particular analysis. As a key point of departure for my analysis, I attempted to identify and evaluate uses of 3D printing which had contributed to a different interpretation than the dominant, developmental, RP use.

In order, then, to extend such an analysis into inquiries on emerging and future uses, it is relevant to ask the following question: What about *emergent* uses which are not easily indefinable, and whose users may not be easily found on a map? While users could be located through conventional sampling methods, it may not necessarily be possible to do so for an inquiry stressing *emergent* use. Additionally, we may need to consider the ways these diverse uses adapt to AM, and how one may better unpack the sociotechnical trajectories of AM by looking at emergent *uses,* human with technical, as opposed to emphasis only on human participants.

In the latter part of this chapter, I will analyse a situated practice that has been conducted throughout this study using a similar structure to that of the relevant social group*s* as discussed in publication 2. However, in the following analysis, I focus on identifying relevant *uses*. I therefore introduce the concept of *emergent use groups*, which is a categorisation of practices similar to relevant social groups, but is instead analysed from the perspective of uses (Figure 33). The concept is meant to locate different societal uptake of AM, such as the use of digital fabrication within medicine, for sports activities or in gastronomy. Emergent uses may also encompass relevant users, in the sense that they provide a particular interpretation of technology, and can be found in similar ways as a sociologist would locate his next research subject.

The emergent use group, however, is more oblique than the former emphasis on relevant users, as its presence may not always be easily located. In this sense, the notion of emergent uses bears resemblance to the notion of *emergent users* from studies of social development. Here, it may be used to describe users who are 'located away from commercial and political centres, and are culturally different not only from the traditional (that is, urban and educated) users but from each other as well'(Devanuj & Joshi, 2013, p. 1) and are thus barely within reach of digital fabrication technologies. Similarly within HCI, studies on the adoption of smartphones by users in developing countries describe emergent users as those who inherit technologies that were primarily designed for users in developed countries (Jones et al., 2017). While they may have access to the gadgets themselves, their use is hindered by the lack of reliable data connectivity.

In relation to my later analysis in section 5.2, emergent uses are formed around the periphery of the known, contemporary use of AM. Much like the non-intended users of smartphones in developing countries, the emergent uses of AM may *inherit,* and subsequently re-interpret, the material characteristics of a given technology. As such, emergent AM uses may be found among individuals or communities which see digital

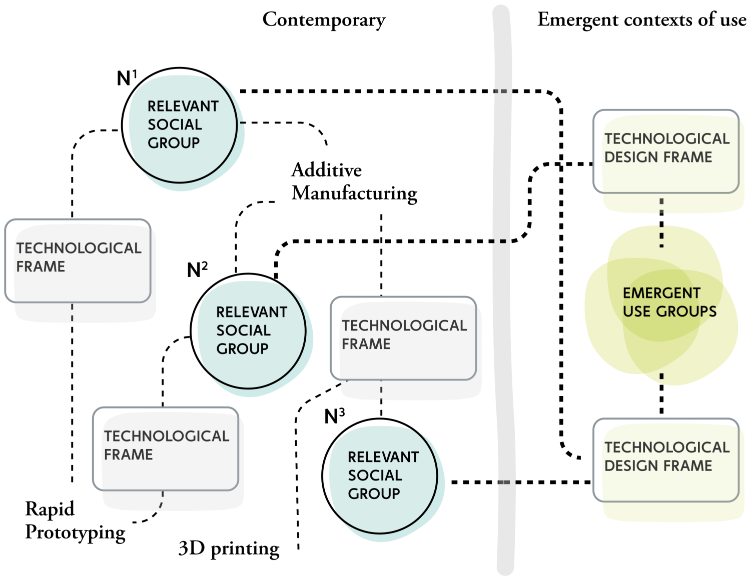

Figure 33 – An illustrative model showing relations between emergent use groups and contemporary user groups. Illustration: William Kempton.

fabrication tools as an avenue for re-evaluating commonly held assumptions on everyday activities. These emergent AM uses might be for 3D printing of gingerbread dough, which adopts parts of the 3D printing toolkit to reinterpret a Christmas ritual; body hacking, which sees personal fabrication as a way to modify human bodily capacities; or entrepreneurial endeavours which see AM as a production platform for ski pole grips which might improve a cross-country skier's efficiency.

Figure 33 aims to illustrate the relation between an identified relevant social group and an emergent use context. As I have argued earlier (see Section 1.2.2), definitions of AM spring out of these different disciplinary interpretations. Terms, such as *Rapid Prototyping, Additive Manufacturing* and *3D printing*, are relative to each users' technological frame. Similarly, the stakeholders within an emergent use group may bring these interpretations into their own technological frame.

As Bijker (1997, p. 123) explains, the technological frame is what enables and structures the interaction among users within a given social group. Therefore, the choice of elements within this technological frame, such as 'key problems', 'goals' and 'current theories' are selected to facilitate a common consensus around a technology. However, for the concept of the emergent use groups that I introduce throughout this study, design activity plays a more foundational role. This attention towards design is reflected in the selection of analytical elements, which are discussed in the following section. The technological frame is therefore named a *technological design frame,* to stress the relation between design activities and sociotechnical analysis. Here, conditions such as 'prototyping strategies', 'material requirements' and 'alternative fabrication methods' play important roles, in addition to those outlined by Bijker (1997).

5.1.3 Sampling emergent users through design

What makes the emergent use group unique, as opposed to an emphasis on actors, stakeholders or relevant social groups, is that it may be revealed through design practice itself. In other words, the individual design experiments and making of activities could be used as sampling methods for locating research subjects and contexts. The objective of this sampling method is to step out of problem-oriented, practical and tinker-dominated role into one that sees its engagements from a broader perspective. The goal of identifying emergent use groups, then, is not to uncover all possible emergences of AM through relevant amateur, craft-oriented or expert users, but rather to emphasise the uptake of AM through the context of use.

5.2 Analysing emergent AM uses

In keeping with the themes of the thesis, I analyse how emergent uses of AM might guide and create new contexts and interpretations of technological use, through their situated practice. As discussed earlier, emergent *uses* may be sampled through acts of design, such as the through design-making critique (see Section 4.4.1). Below, I initiate an analysis of a situated use of AM to understand better how it contributes to a contextualised view of sociotechnical development.

Specifically, I look back at particular practice from within the thesis research, namely the 3D gingerbread project. As I introduced through the methodology chapter (see section 3.4.5), the 3D gingerbread project dealt with reinterpreting the Scandinavian Christmas ritual of making of gingerbread houses through digital fabrication tools. Relying on a set of pre-existing tools and techniques, new technical configurations were designed to make it possible to 3D print gingerbread dough. Through this case, I intend to put into relation and build a perspective around the various analytical concepts introduced, such as emergent use groups and technological design frame.

5.2.1 A technological design frame of analysis

Before visiting the above-mentioned case, I will first explain the *technological design frame* which structures the analysis of emergent use. As mentioned (see section 5.1.2), this frame allows me to make common points of reference, as it did in the previously mentioned study. Here, relevant users in the development of 3D printing devices were discussed within a common framework which structured the interaction among groups. As such, the frame functions as a way of analysing the scripts, or inscriptions, which are designed into a technological device in anticipation of it performing a certain action (Akrich, 1992). According to Hanseth and Monteiro (1998), such inscriptions may be analysed according to the envisioned scenario, the material that 'inscribes' and the strength of the inscription. These aspects have been brought into my design-centred analysis and translated according to the context of this analysis. The strength of an inscription is understood as the way it is perceived to be implemented. The components of the technological design frame are explained in Table 5 below.

Table 5 – Technological design frame

Envisioned contexts of use	Where is the emergent use located?
Technical agency	Which are the relevant technical characteristics of the technologies used?
Technical challenges	What are the technical challenges in relation to the envisioned contexts of use?
Relevant user groups	Which actors or stakeholders are potentially relevant?
Methods and prototyping activities	What kind of methods and prototyping activities have been used in the process?
Relevant scenarios	Which cultural features or traditions does the design build on from?
Use of tools	What are the relevant tools, and how are they brought to use?
Perceived implementation challenges	What are perceived implementation challenges in relation to the relevant users, scenarios and technical challenges?
Alternative fabrication methods	How else could the goal possibly be reached, using alternative fabrication methods?

Notably, the components of the frame in Table 5 are not definitive. As with Bijker's (1997) technological frame, which influences this framework, the framework can be supplemented with components that are relevant for the

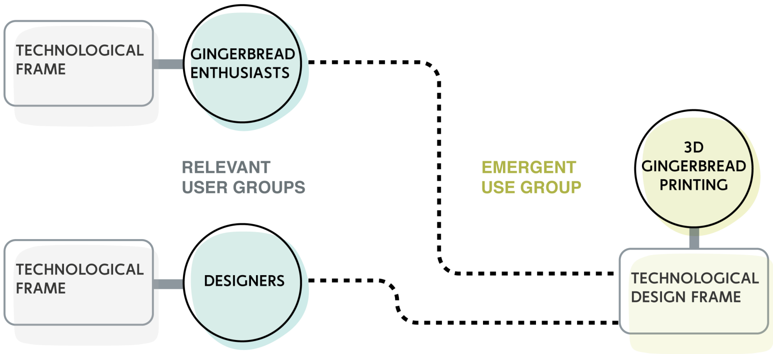

Figure 34 – Illustrating how the 3D gingerbread printing may relate to identified, relevant user groups. Illustration: William Kempton.

particular analysis. As an example, I have included *alternative fabrication methods* as a way to discuss and open for an alternative use of fabrication tools. This component may not be relevant, however, when used to analyse other emergent technological domains. In discussing internet-enabled devices for quantifying biometric data, which Greenfield (2017) incorporates in his discussion of radical technologies, it could be more relevant to talk about alternative measuring techniques. As such, the choice of components must be considered in relation to the objective of analysis, as well as the way the technology is interacted and engaged with.

5.2.2 The 3D gingerbread project

Looking back at annotated design processes discussed in the section on research data (see section 3.4.5), I reactivate the 3D gingerbread project which was carried out in the months preceding Christmas 2016. The project focused on renewing the Christmas ritual involving the making of gingerbread houses, a ritual often performed in Scandinavian homes.

As Figure 34 shows, 3D gingerbread printing interprets 3D printing through the framing of a gingerbread enthusiast and designer use. These relevant user groups have been identified and discussed in prior publications (publication 2). Figure 34 makes relations between user groups such as designers and laypeople, with *emergent uses* such as 3D gingerbread printing. Relevant user groups can be understood as overarching because they provide useful interpretations of a given technology, which may influence how it is perceived and used. The *technological design frame* makes it possible to see common patterns in the interaction among users, as it sets out to establish strategies, actions and methods which is heavily influenced by design practice. Having now identified relevant users for this case (Figure 34), I will elaborate on how this project can be understood as an *emergent* use of AM.

Table 6 – Technological design frame for the 3D gingerbread printing

Envisioned contexts of use	The project is envisioned as a Christmas activity for a primarily domestic context.
Technical agency	Liquid Deposition Modelling (LDM) makes it possible to extrude liquid materials such as gingerbread dough.
Technical challenges	The three-dimensional form is constructed of raw dough before being baked in an oven, which makes it easily collapse while in the oven.
Relevant user groups	The conceptual nature of the project relates to a design-context through its designerly approach. However, the project is viewed as relevant for bakers and gingerbread enthusiasts.
Methods and prototyping activities	A design for the stave church was made in CAD and evaluated in PLA (Polylactic acid) plastic on a desktop 3D printer. Then, batches of gingerbread dough were mixed and tried out in the LDM extruder. Following the initial trials, both the digital model and LDM extruder were modified to take into account the viscosity of material, angle overhangs and internal support structure.
Relevant scenarios	The 3D gingerbread house takes the popular Christmas ritual of making gingerbread houses and reinterprets it using digital fabrication techniques.
Use of tools	Desktop 3D printing tools are used to fabricate edible gingerbread dough. Digital design techniques, such as CAD modelling and conventional RP, have been facilitate the process.
Perceived implementation challenges	Apart from the technical challenge of the raw dough collapsing, the technique of 3D printing gingerbread dough requires potential users to have access to adequate technical skills in terms digital drawing. In addition, they will require access to a 3D printer capable of fabricating with gingerbread dough.
Alternative fabrication methods	The project builds on the existing ritual of making gingerbread houses through conventional kitchen appliances. In terms of digital fabrication, it is possible to laser-cut readily baked sheets of gingerbread based on a digital blueprint.

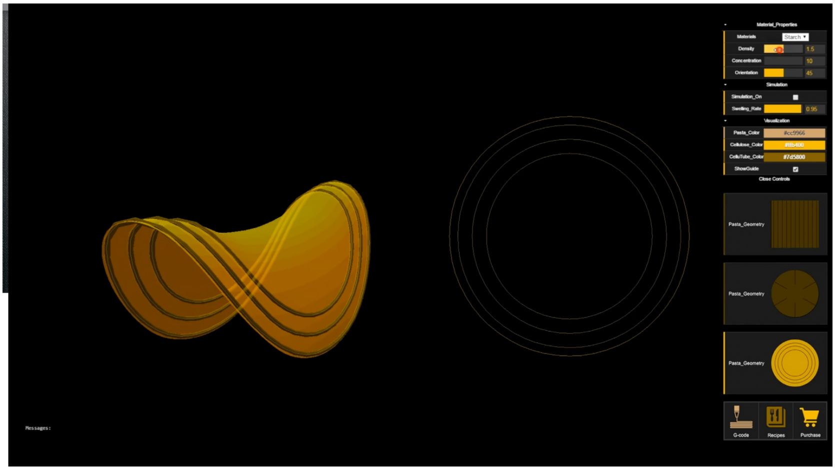

Figure 35 – Novel AM techniques are applied to allow pasta figures be reshaped through a use interface. Image caption from promotional video. Photo: Wang et al., 2017

Before describing the project through a technological design frame (Table 6), I will briefly recount why I see the 3D gingerbread project through the perspective of emergent use. First, it is important to acknowledge that an underlying ambition of the project was to explore materialities other than those commonly found on personal 3D printers, such as hard or soft plastics. There is in fact growing interest in developing other, desktop-friendly materials such as metals and ceramics, although these processes usually involve the use of a kiln or a high temperature firing oven. Second, it was my ambition through the projects to develop a better understanding of how to digitally fabricate edible materials such as the gingerbread dough.

The use of edible materials within the AM process is arguably a field of growing interest, as research labs, commercial entities and individuals are investigating ways of producing edible food using 3D printers. As the majority of edible, fabricable materials consist predominantly of melted sugars, such as with the 3D Systems' ChefJet, they remain largely ornamental in function. Culinary food 3D printers such as Foodini are presented as kitchen appliances which may help in the process of preparing homemade food. Other initiatives, such as the Transformative Appetite project from MIT Tangible Media Group (Figure 35), have developed a suite of materials and computational software for printing short pasta (Wang et al., 2017). The pasta, which is additively joined with an ethyl cellulose on a flat surface, is transformed into a curved volume when boiled according to a predefined plan. The concept, which demonstrates how culinary experience may be optimised by novel technologies, must be seen as a futuristic vision on how one might engage with AM in both the kitchen and develop new taste.

The increasing amounts of projects and initiatives taking on cookery with digital fabrication tools embed visions of how AM technology might be made useful in newfound, non-conventional ways. However, little emphasis is placed on scripting them in relation to everyday user experiences. While it could be argued whether or not the 3D printing gingerbread project addressed this challenge of implementation, it sought to engage with a cultural phenomenon (a Christmas ritual) which was conveyed through explanatory videos and an exemplary artefact. The 3D gingerbread project stressed a use of tools (from the dough ingredients and kitchen aid, to publically available CAD apps and desktop 3D printers) which were considered to be within reach of the relevant users. The way the project was communicated was also in line with the, through the sharing of files and step-by-step online instructables.

By contrast, the Transformative Appetite project (Wang et al., 2017) is conceptually implemented into a high-tech, high dining experience. This is reflected in the use of parametric tools (Figure 35) which allows users to reshape pasta figures.

The development of the gingerbread project aligns with *design-making critique* as an approach to technological inquiry. While it started off as a designerly approach to engaging with 3D printing tools through the introduction of novel materials, such as *how* to fabricate gingerbread dough, concerns were increasingly oriented towards *what* such an attempt could illustrate. As soon as the project was set in a public context as a speculative design concept, matters soon oriented towards the question of *why* such a design could even exist.

The way the design was perceived, as seen through online commentary (see section 3.4.6), is necessarily a process of subjective reinterpretation. As such, it could be criticized for being viewed as a process of replacing our own handcraft capacities with an automative technology, even in a time of Christmas joy. The point of emphasising these unintended perceptions is precisely to illustrate that a design conceptualisation was necessary for reflecting on the scripts related to the Christmas ritual, as well as the conceptual implementation of the 3D gingerbread project.

5.3 Towards a model of Design-Making Critique

I will now recall key concepts in order to advance my holistic model of design-making critique. In the second chapter, I located a version of product design as being oriented towards a *critical* and *future-driven* form of inquiry. Having discussed the way in which product design development is predominantly conceived of as a market-driven practice, I departed from this view through a review of relevant, speculative and inquisitive approaches to design, which questioned the very relationship between our everyday lives and the technologies we encounter. In my review of theories of sociotechnical change, I discussed *non-determinism* through the concepts *inscription* and *materialisation*, which relate design activity to technological analysis. These perspectives were then used to review and critique how AM is discussed in relation to utopia and dystopia.

In the fourth chapter, I stepped further into how design contributes to an interpretation of AM through craft practice. I related this discussion to theories of learning, with an emphasis on constructionism as a framework for building knowledge through experience. Specifically, I talked about the experience of making and the artefactual prototyping practices that are involved in the process of doing design. I then introduced a preliminary model of learning both *with* and *through* AM.

Coming out of the fourth chapter, I introduced a critique of Ratto's (2011) critical making framework, which brings design methods into theoretical contemplation, while placing little emphasis to the design object. While Ratto (2011) understood critical making as a process of analysing theories through making, I introduced the concept *of design-making critique* as an approach to embedding technological critique within the process of developing new designs. This approach takes a holistic, experiential approach to product design which jumps in and out of technically and socially oriented conceptualisations of design.

As an analytical framing to such an approach, I introduced the concept of a *technological design frame*, which builds on analytical frameworks of technological development (Akrich, 1992; Bijker, 1997; Hanseth & Monteiro, 1998). While the approach is introduced to stress a design-oriented approach for technological envisioning, the analytical frame is envisioned to support the theoretical analysis of how *emergent use groups* create their interpretations of emergent technology. Based on the definition of an emergent user as someone who is 'barely within reach' (Devanuj & Joshi, 2013), I argued that just as a sociologist may have various methods of

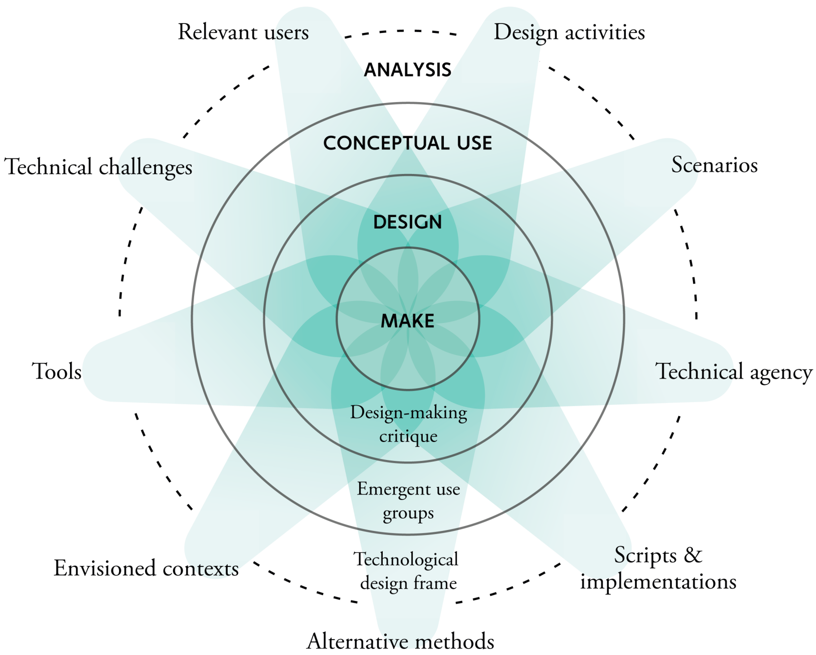

Figure 36 – A model of design-making critique. Illustration: William Kempton.

sampling users, a design analysis may be formed using its own practice as a sampling method.

Throughout chapters 4 and 5, I introduced concepts for discussing design, conceptual use and analysis. These concepts were defined as the technological design frame, emergent use groups, and design-making critique. Seen together, they form my overlaying unpacking of the concept of making. The holistic model of design-making critique, illustrated in Figure 36 places all the above-mentioned concepts in relation to one another.

With making as its core and integrating activity, this model connects making, design, conceptual use and analysis. Respectively it moves from design-making critique through emergent use, into a wider technological design frame. These elements shown within the concentric circles of the model, are relational and form a wider assemblage. The outer rings of the model present the diverse means, contexts, tools and memberships in the making of making actual. Elements may overlap, cohere or diverge; they may be configured in various patterns that are clustered or asymmetrical.

Elements from the outer circle may also move with varying force and concentration towards the core activities of making. In reflecting on my own visualisation, it is relevant to consider why they are visualised as they are. Furthermore, what does the model show us?

The model recalls a developmental timeline which is concentric rather than linear. The importance of this is that it may intervene with generating insight into the technical materials of AM, and apply them to a contextual design process. As it is not restricted to the temporarily of development or the bias of artefacts, it can be read from outside in, or inside out respectively. A similar concentric model was introduced with Figure 11 which illustrated the study's methodological perspective, consisting of different methods, techniques, tools and themes. Equally, the model of design-making critique resembles a world-view on the relation between making as DIY practice and culture, with design practice, and technological studies and inquiry.

Through this world-view it brings to AM an attention to critique and reflection. In particular, it is relevant for a design pedagogy which seeks to give meaning and use to technical characters. In doing so it is also relevant for unpacking emerging technology, as I argue there are social and technical implications to how technologies are materialised, such as those produced by AM. Having claimed its relevance in product design practice, it can be argued the model does not thoroughly guide prospective users towards how to initiate making, nor offer advice on which *new* ideas can be made through AM. This, however, not the scope of the thesis. Rather, it is seen as complimenting existing design techniques, methods and a host of richly illustrated narratives for ideating on and conceptualising designs.

5.4 **Designing through emergent and future uses of AM**

The ability of design to articulate on future uses of technology, is in my opinion a highly relevant topic to discuss. Designers are arguably in close proximity to the technical resources which need to be plied and composed to form a functioning device. The rules in which this composing takes place, is strictly guided by the technical resources, perceived use and through the materiality of the technical resources. As I perceive it, by practicing design, designers take on the role of technological negotiators. Without any technical resources at hand, there can be no design. Therefore, considering design practice as an exercise in shaping technology might at first glance come off as a redundant remark. This perception, however, relates to a perception of technology restricted only to the tools, materials and technical resources which are, at most, a visible spectrum of technology.

As I have sought to convey through this exegesis, a larger technological space comes into play as tangible technical resources are brought into use. As I have accounted for, technology is seen as technical, but also as cultural and organizational aspects of technological practice (Pacey, 2004). As such, technology governs both the economic and industrial activities with which we engage and the ethics and values by which we live.

Design, then, is not just about the shaping of artefacts, but it is also about relating to the complex social outcomes of the design process. As Winner (1983, p. 253) reflects on in his discussion of technology, the knowledge of how cars are made and operate, and the traffic laws that govern them does little to help us understand how they affect our modern everyday lives. In other words, mere attention to the technical artefact and the requirements that surround it does not necessarily help us arrive at a clearer understanding of the conditions that unfold as we incorporate the artefact into our lives. As his discussion leans towards an attention (or lack thereof) to a philosophy of technology, so does my overlying discussion lean towards an attention to the capabilities that lie at hand in using design methods to reflect on technological speculation.

This is not to say that design practice, as performed by professional designers, has the sole responsibility for shaping technologies. As I have discussed earlier (see section 5.1.1), the network of technological stakeholders is vast, and I see design as serving only a particular role. However, this role is, in my opinion, key to getting a more situated understanding of unforeseen consequences and hidden power structures, through critique and contemplation. These factors may be brought into light through the practices that designers are often known to do well in articulation through making.

As Feenberg (2008) points out, designers do not work in a vacuum. Design is inherently restricted, and designers must negotiate their conceptions within the template of social uptake, hierarchy and power structure. The design space, as Feenberg (2008) describes it through his instrumentalisation theory, is a matter of combining and organising a given selection of technical elements. These elements, which are relatively neutral and free of constraints, are then combined under a technical code to construct a concrete device, which are full of constraints and biases. This is where the instrumentalisation process come into play. This process, as I explained in relation to his critical theory of technology, is a process of 'reorienting and integrating the simplified objects into a given natural and social environment' (Feng & Feenberg, 2008, p. 113). Feenberg's (2008) discussion on design and technology culminates into a way for designers to draw keener attention to the background assumptions of our technical heritage. According to Feenberg (2008), this questioning of technology may help us open areas for designing technology differently.

Returning to the question of why design investigation is relevant for critiquing the development of AM, I see it as imperative for design to promote the values contained within the repertoire of AM, rather than strictly adhering to standards to which they are currently subjected. Such standards include those that promote methodologies in designing *for* AM as an industrialised production method. These methodologies, predominantly coming out of the technical domain of AM, seek to promote and optimise the latent features of the technique; these features, which are well versed within the literature on AM, are often described as *mass-customisation* (Bertling & Rommel, 2016)*, topology optimalisation* (Zegard & Paulino, 2016)*,* or *multi-material design* (Oxman, 2010).

Notably, there is an increasing amount of research offering many valuable contributions on technically inclined AM methodologies. For example, the capacity to reduce and consolidate parts within the production of jet engines could have a direct influence on next generation airliners with reduced fuel consumption. An appropriate design methodology for these kinds of AM contexts could help the actors involved in the design and production of such technologies actualise their work. However, these frameworks do little to guide us in conceptualising alternative designs, which may also be articulated *through* AM.

This argument also corresponds with the lack of consensus about what it is that AM may be seen as *doing* in a near future. The notion of the 'killer app', in that a single, dominant use application will gradually be affiliated with its existence, is still evident in debates on AM and 3D printing (Unruh, 2015). This attitude towards emerging technology is in my opinion only a restricted view on what is a vastly opaque technological phenomenon.

Based on the discussion of emergent uses of AM and the making of alternative visions, it is evident that unintended, or even unwanted, outcomes could be brought into light. A notable example of this is the Liberator gun project by Cody Wilson and Defence Distributed (Wilson, n.d.), who successfully designed a personally fabricated, non-detectable plastic hand gun capable of firing a .380-calibre bullet. The project, which Wilson himself describes as *making* a political act (The agenda with Steve Paikin, 2013), brings into discussion issues of gun regulation and decentralised production, making visible the larger spectrum of technological activity. In taking up this debate, Ratto also questions the ramifications that such a technology might have on ballistic forensics, as the gun might not fit with standard procedures of testing (The agenda with Steve Paikin, 2013).

5.4.1 AM as an evolved phenomenon of artefacting

Is AM a completely new phenomenon? The answer to this can be both yes and no. As there has never previously existed a technological platform which harnesses computer-generated geometry and churns it into a physical form, as directly and with as little operational detour as a 3D printer, AM is a relatively novel concept. However, the act of fabricating unique artefacts directly into shape based on a predefined template is not unique.

A colleague once commented, tongue-and-cheek, that '3D printing is essentially a masculine form of knitting', referring to the many commonalities between the two techniques.[4] Just as knitting relies on spools of thread, so do the contemporary techniques of personally 3D printing plastic artefacts. The spools of woollen thread and plastic filament are often bought in specialist shops, organised by colour or material composition. Just as a knitting enthusiast might decide to use a soft blend of woollen thread for an upcoming mitten project, the equivalent 3D printing enthusiast may desire a bamboo-filled biopolymer for her door handle design.

Aside from materials selection, both phenomena attract a considerable amount of communal sharing, organising courses and sharing guidelines or templates for concrete projects. Just as CAD files and .stl files for 3D printing are shared on sites such as thingiverse.com, knitters sign up to sites such as ravelry.com to share knitting or crocheting patterns.

While the obvious differences between hand-based knitting and personal 3D printing can be seen in the latter phenomenon's dependence on computational hardware, developments in knitting are increasingly tied in with digital tools. Hardware projects such as Kniterate seek to leverage fashion fabrication by developing digital knitting machines that could fit on a kitchen table. The project, which was successfully crowdfunded on Kickstarter in 2017 (Kniterate, 2017), is presented as being capable of knitting scarfs, shoe uppers, woollen hats, tank tops and sweaters based on individual designs. As opposed to a personal 3D printer which fuses material

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[4] The fact remains that knitting has a longstanding history of male participation. From the knitting guilds that rose in central Europe in the 15th century, to the current resurgence in male knitting. In fact, the UK alone exported some 240 000 pairs of stockings to Normandy in 1663 – a vast majority produced by men (Mike, 2015).

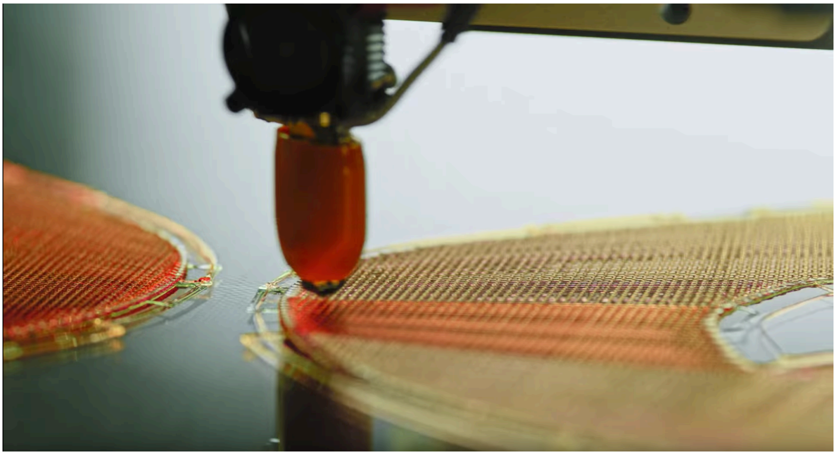

Figure 37 – Spools of thermo-elastomer are fused in a fabric-like pattern to make the shoe-uppers of the Nike shoe, using their newly developed Flyprint technology. Photo: Nike press release.

through direct exposure to light or heat, the knitting machine bonds and stitches its thread through a series of individual gauges.

Within industrial applications, these processes are even further entwined, as sports companies such as Nike, Adidas and Under Armour seek to incorporate knitting techniques and 3D printers into their production platforms. Products such as Adidas Futurecraft 4D sneakers and Nike Flyknit technology embed both complex knitting technologies and 3D printing techniques within their process of fabrication. As a statement on how they see the processes of 3D printing and knitting as co-evolving, Nike released a press statement on its most recent advancement in shoe production (Nike, 2018). The Flyprint, appropriately combining its existing Flyknit upper-shoe knitting technology with 3D printing, is revealed through a video clip in which spools of filament are extruded out to form an open mesh-like structure, as shown in Figure 37.

The shape, which reveals itself as a pattern for an upper-shoe, is carefully scraped off the build surface, inspected and stretched before fading over to a preview of an assembled shoe. the heated nozzle for extruding molten plastic. Spools of plastic filament. A spatula for scraping the fabricated artefact off the build plate. Bringing in technical cues from digital desktop fabrication such as these, the video makes a strong rhetorical move towards open-source values, customer involvement and tailored production.

In summing up, it could be asked why this comparison is relevant for interpreting future visions of AM through design intervention. By comparing the two processes 3D printing and knitting, I want to convey that the uptake of AM must be understood better in conjunction with existing technological spheres. This is not to say that it relies on metaphors and technological comparisons for conveying its own development, such as the one just made between knitting and 3D printing. Rather, I argue that the technical characteristics of AM must be treated as only part of a larger picture that relates to social interpretation. The concepts I have introduced through this study can then be seen as tools to gain new perspectives through design.

5.5 Pedagogical implications for design views on AM

The research project is primarily conducted within an educational context, using students, studios and laboratory facilities as resources. As such, attention is given to the application and development of new learning theories on design. Through my research methods I have observed prospective designers engaging with design techniques within an educational context. These observations, alongside my own research practice, have been valuable for developing my research contributions, such as the *design-making critique* as an approach to reflecting on technologies through acts of making. Specifically, this approach is emphasised as one that reflects on the application of tools (such as 3D printers) through an experiential learning cycle. Moreover, the approach is presented in a series of stages, from reflection on the process of making, to the critique of what design proposals and making practices do as a form of knowledge inquiry.

This newly introduced design approach is grounded in two complimentary conceptualisations of design, cycling between socially oriented (exemplified through Critical Making) and technically oriented (exemplified through RP and Design for AM) frameworks, which I have argued are core to building a critical perspective through design. While the approach is explained through models and cases of how to perform design research into topics such as AM, as an overarching model, it lacks a specific guideline in terms of how it could be employed in design education. This is a gap I have tried to address in this thesis.

5.6 Implications for research on AM

The initial focus of the thesis has been to direct attention away from the technical, production-oriented uptake of AM technology. This focus is briefly unpacked in the introduction, where I emphasise the need to shift AM from a technical interest to a broader social interest. The background for this focus has been the dominant model of AM inquiry, which is tied to industrial manufacture and scientific inquiry, and ranges from the development of novel materials to the generation of economic business models. The aim of the thesis has therefore been to frame and orient AM inquiry into product design. Specifically, the emphasis has been to develop the notion of making as a form of designerly learning, which enables it to confront sociotechnical change.

Having addressed the thesis' argument through newly introduced concepts, I will now step back to the point at which this thesis departs. Specifically, I will discuss AM in relation to the future of industrial manufacture.

Links have already been established between AM and its relation to the overarching topics of political or economic concern (Ratto & Ree, 2012; J. Stein, 2017; Troxler, 2014). These links are discussed in Chapters 2 and 5 of my review of technological claims through concepts such as the *third industrial revolution.* Briefly summarised, this anticipated revolution is a new industrial paradigm which is characterised by a series of advances in emerging technology such as Artificial Intelligence, robotics, nanotechnology and AM. It also appears through labels such as the *fourth industrial revolution* or *Industry 4.0*[5].

As with the emphasis on digital and computational technologies in the current paradigm of industrial manufacture, the next paradigm is said be driven by increased overlaps between digital technologies and physical systems (Schwab, 2017). The claimed reason for it not just being a continuity of the current paradigm is that it is characterised by the velocity and scope in which technological developments occur. Whereas the previous industrial revolutions were carried out at a linear pace, the next revolution is said to be exponential in growth. And while it is said to have the potential to increase the quality of life through introducing better services and products, scholars have warned that it could create greater divides between those who have access to those services and products, and those who do not (Brynjolfsson & McAfee, 2012).

Blending into this discussion, I see it relevant to consider some of the broad socio-economic discussions that relate to emerging technologies such as AM.

[5] Notably, the World Economic Forum Annual Meeting of 2016 was devoted to the theme of *Mastering the Fourth Industrial Revolution.*

The fact remains that manufacturing historically ties in closely with the construction of economic wealth. Just as Britain rose to become a leading commercial nation following the 19th century industrial revolution, manufacturing-led innovation enabled the US to claim itself as an economic superpower following the Second World War.

5.6.1 AM in the field of Advanced Manufacturing

In a recent book entitled *Advanced Manufacturing* (Bonvillian & Singer, 2018), the focus is oriented towards the innovation policies that guide the American manufacturing sector. The backdrop to the discussion is the Great Recession following the 2007 financial crisis, which had severe consequences for the US manufacturing industry. The collapse of the auto industry, including that of General Motors(GM) and Chrysler and the offshoring of entire industries to low-wage countries such as China, caused the decline of millions of manufacturing jobs.

Advanced Manufacturing (2018) introduces core topics which are relevant for research on AM. The first is that there could be new production paradigms that have the capacity to transform the manufacturing sector. A central claim is that current manufacturing sector is deeply entrenched, like many other legacy sectors (utilities, infrastructure, education etc.) that provide occupations for a large amount of US citizens. These sectors are characterised by the prevalence of *subsidies and price structures* which favour those who manage it, *vested interests* that protect the sector, *knowledge and human resources* structures that cater for the needs of existing technology, and *limited research and development* which neglects to implement new innovations.

The other major topic is that the current emphasis on entrepreneurship- and start-up models is not easily transferrable to technologies that require manufacturing because they often involve higher risks than developing software. While the American manufacturing output declined around the turn of the millennium, its dominant role in the IT sector skews innovation policies towards the mindset of 'innovate here/produce there'. The challenges, as the authors claim, is that outsourcing the production know-how can easily lead to a model of 'innovate there/produce there', as the complex systems and suppliers and expertise move offshore (Bonvillian & Singer, 2018).

The book takes interest in AM as a technology that is core to the development of new, innovative production paradigms. It is discussed in relation to the *America Makes* consortium, which is a joint programme between a series of corporate US enterprises and research institutions, including Honeywell, Boeing and General Electric. The program, which launched in 2012, is seen as an example of the extensive and long-term investments that need to be made to foster such a changing production paradigm. Additionally, arguments are made for AM which touch onto a debate on Mass Customisation. Citing the *Production in the Innovation Economy* study by MIT (Locke & Wellhausen, 2014), the model of 'economies-of-one' is seen as a feasible alternative, where 3D printing and computational techniques provide the basis for creating tailored, unique artefacts.

5.6.2 Modelling AM around sustainable values

While publications such as *Advanced Manufacturing* (2018) provide useful socio-economical perspectives to research in AM, there is an ongoing need to compliment them with critical accounts of how they are carried out. The book uses the model of the hourglass to describe how the manufacturing sector creates a vast infrastructure of suppliers, resources and R&D (top part of hourglass), as well as distribution, sales, servicing and product life cycle (lower part of the hourglass). Similarly, the future uses of AM could be evaluated using the same model. However, the values that describe the model need to sustain the potentially wide-ranging uses it promotes. As I have discussed throughout, the belief that a single 'killer-app' for AM is yet to arrive is indicative of a restricted view on a vastly opaque technological phenomenon. In making a model such as the hourglass, it is necessary to ask how AM may be sustainably integrated with ways of making things. Further, we need to ask how AM might valuably complement existing practices, and what incentives there are to do so.

6 Conclusion

From a product design perspective, research is now emerging into shifting from focus on materials and technologies such as in engineering, to development and experimentation with design-based views on emerging technology. As James Bridle (2018) warns us, ‘All too often, new technologies are presented as inherently emancipatory’ (Loc 108). To consider Advanced Manufacturing, and thereby AM, a carrier of socio-economic change is challenging.

The overall objective of this research inquiry has been to explore the emergent uses of AM by way of product design making and reflection. Seeing how the uptake of AM occurs between new technical developments and through emerging social interpretation, I have integrated practice-based design inquiry with theories on sociotechnical change. In doing so, I orient product design towards a constructive practice for reflecting and articulating views on the emergent social uses, interpretations, qualities and characteristics of AM technologies.

The study has been developed through a RtD approach, which emphasises the role of practice-based research for inquiring on AM technology. Specifically, my methodological approach combines qualitative research methods with design development techniques and 3D printing tools. The qualitative data that has been generated through this approach includes annotated design processes, fabricated artefacts, curated installations and participant observation of both students and experts engaging with design. These data address the following overarching research topics: (a) emergence of AM, (b) product design expertise and (c) technological critique.

In this chapter I first offer several personal reflections as a designer-researcher. I then reiterate the core argument of the work, following which I outline the main contributions with reference to (1) a critique of the sociotechnical transformation of AM from within the product design field, (2) the incorporation of theories of socio-technological development into

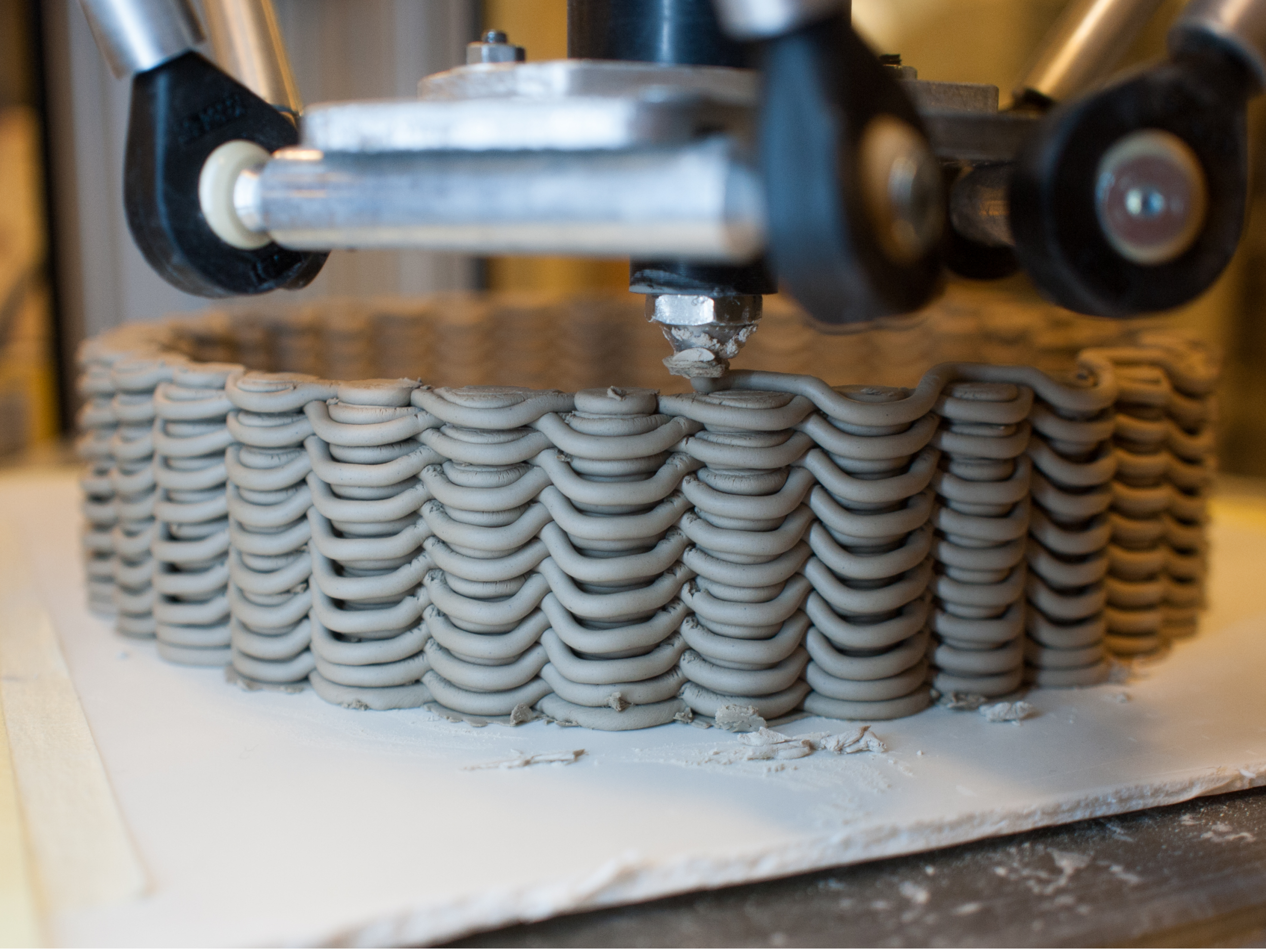

Figure 38 – A desktop 3D printer in the process of 'weaving' clay. Photo: William Kempton.

design pedagogy, and (3) a realignment of critical making approaches with design expertise.

6.1 Personal reflections

As I write these concluding lines to the thesis project, I realise how not only my perception of doing design research has evolved, but also my interpretation of AM technology. Still vivid are my first personal encounters with a 3D printer during the second year of studying industrial design at AHO in 2009. At this point, my understanding of AM was still obscured by the heavy steel structures confined behind the closed doors of the RP laboratory. Observing the machinery, all my thoughts were shrouded in the idea of the mysterious device appeared physically and imaginatively as a 'black box' cloaking a set of seemingly expensive and highly complicated processes. The RP machine was a mysterious device, magically churning out cutlery designs in a powdery white finish of the SLS machines.

It was not until I started engaging with desktop-style 3D printers some years later, in 2012, that I could really start to question the ways in which to engage with the RP capacities of AM technology. Assembled from smelly, laser cut pieces of plywood and Arduino prototyping boards, my own Ultimaker Original, affectionately named Ursula, was a noisy, visceral device which immediately called for my attention. Contained in a size that would fit on a kitchen table, it was a stark contrast to the tools at the schools' RP facilities. With my own fabricator at hand, I could watch and interpret its movements as the heated nozzle made outlines of my digital tinkering.

Not only did this observation allow me to see and adapt my technique to the many quirks of the process, but it also invited a great deal of mechanical adjustment. As an early adopter, I subjected myself to a lengthy, incremental process of frustration and improvement, as my online peers began to publish and propose hardware and software improvements for the 3D printer. Embracing an open-source model of hardware development, newly established companies such as Ultimaker involved users' contributions into their development strategy. Updates and components to the device would sport names such as the Olsson heated block, named after community-members who helped develop a component specific to its function and identity.

Looking at the current offerings of many desktop-oriented 3D printers, they seem a drastic departure from the modest, customer-assembled kits which were briefly the norm of personal 3D printers. The smelly laser cut plywood and modified Arduino boards of the original Ultimakers, Makerbots and countless others have since been replaced by die cast metal components, wireless data transfer, touchscreen interfaces and self-adjusting mechanisms. More importantly, the tools have become predominantly preassembled, constructed by the same logic as an equally sized kitchen appliance. As Figure 2 at the start of this thesis illustrates, promoted uses of desktop 3D printers are even in reversal, from early visions of increased domestic consumption, and back to its formal audience – to designers or engineers who use it in their working processes.

This research project springs out of a curiosity for how desktop 3D printing could be perceived for domestic consumption, much like that of a kitchen appliance. As a design student, I became interested in how I could make use of the tool for replacing, repairing, playing, decorating and most of all, supporting me with my own design projects. Having followed the rapid release and re-release of so many home-oriented 3D printing devices, my attention soon shifted towards the underlying questions that seemed not to have any easy answer (As for my query on its purpose in a domestic environment, my attitude was somewhat reluctant). Why did 3D printers develop into desktop-friendly devices, who was involved with making them so, and what would be made out of them if domestic uptake of the technology was not as initially intended. Moreover, what could I, from the perspective of design practice and expertise, do to investigate this phenomenon of technological adoption.

6.2 Thesis argument

At the centre of this thesis lies an argument that designing for AM needs to be supported by critical reflection of the technical capacities of AM because they are subsequently subjected to interpretation through their social contexts of use. Specifically, I contend that the practice of *making,* as an experiential activity, has the capacity to situate, and therefore reflect on the implementation of the technical capacities which are envisioned for AM. Here, the concept of making is emphasised as one which encapsulates both practical inquiry and the activity of knowledge transformation. This it does in order to question the social and technical agency that adheres to AM technology.

The overall argument that develops through this exegesis is supported by the findings from underlying research publications which state the following:

- Attention needs to be refocused from engineering-oriented Design for AM frameworks to a design-centred perspective on AM. This is exemplified through a series of conceptual artefacts which show a detailed scope of the designer's role in a product development process (publication 1).
- Analyses of relevant social groups to AM reveals a distinct understanding of what the 3D printer does in relation to design. While a business perspective on AM might centre a shift from mass-production to individual production, layperson interest might be interpreted from a perspective of technological empowerment (publication 2).
- Such a cross-disciplinary interpretation subsequently influences the prototyping strategies which are performed through AM. Through the observation of expert designers, I discuss how relating digital design activities to product design moves emphasis from prototyping as a conceptual embodiment to the making of saleable products (publication 3).

- Seeing how AM tools are able to facilitate such a transition from concept to implementation, attention needs to be placed on experiential learning models for generating knowledge *through* AM (publication 4).

6.3 Contributions

The study makes the following contributions:

- It critiques the sociotechnical transformation of AM from within the product design field.
- It incorporates theories of socio-technological development into design pedagogy.
- It realigns critical making approaches to design expertise.

Building on theories and analyses which have been established through the publications of this PhD study, this exegesis contributes with a set of novel concepts for approaching and analysing the *emergent uses* of AM. Building on established terms of embodied design critique and 'Critical Making' (Ratto, 2011), I introduce the concept of *design-making critique* as an approach to a designerly, technological reflection. Based on an experiential learning approach, the concept cycles between different conceptualisations of design to develop knowledge around the technical and social characters of a technology. In doing so, it facilitates an approach which is oriented towards future technological development.

At a preliminary stage, design-making critique emphasises reflection on the application of the design methods, how prototype exercises are performed and ways through which they can be employed in the development of a design. Attention here is placed on the discreet functional and aesthetic qualities of a design, how a design is perceived in use and how it may subject to misuse. In doing so, it questions the application of methods used and how they can be strategically applied to confront such issues.

At a secondary stage, design-making critique connects design activity to the practice in which the critique is being made. Placing attention on a plausible vision of the future and alternative scenarios which are extrapolated from cultural and social references (Auger, 2013), the secondary stage sees emerging technologies as a playground for making future speculations and anticipations. In this way, these speculations translate into an embodied form of a design-making critique which is communicated *through* its design and experimental artefacts.

At a third stage, design-making critique turns its attention towards its role in shaping and interpreting sociotechnological developments. To do so, the designer must consider the underlying assumptions, goals, technical components and applied uses of design methods which are brought on by designers and makers alike.

In the context of this research by design project, design-making critique is introduced as a designerly way to sample subject-matter to conduct a formal research analysis. Just as the social sciences develop and use a variety of sampling methods, I argue that design research should be capable of fashioning samples from within their own practice. These subject matters, which I call *emergent use groups*, are then discussed and analysed according to an analytical frame. This framing is labelled the *technological design frame* and consists of several elements for describing characteristics such as *envisioned contexts of use*, *technical agency*, *methods and prototyping activities*, *relevant scenarios* and *perceived implementation challenges*. As the framework is intended for analysis of sociotechnological phenomena, it may be subject to change depending on the particular investigation being made.

PUBLICATION 1 – DESIGN ISSUES AND ORIENTATIONS IN ADDITIVE MANUFACTURING

Killi, S., Kempton, W. L., & Morrison, A. (2015). Design issues and orientations in additive manufacturing. *International Journal of Rapid Manufacturing*, *5*(3–4), 289–307.

PUBLICATION 2 – A DESIGN SOCIOTECHNICAL MAKING OF 3D PRINTING

Kempton, W. L. (2017). A design sociotechnical making of 3d printing. In S. Killi (Ed.), *Additive manufacturing: Design, methods, and processes* (pp. 21–74). Singapore: Pan Stanford Publishing.

PUBLICATION 3 – THE IMPACT OF MAKING: INVESTIGATING THE ROLE OF THE 3D PRINTER IN DESIGN PROTOTYPING

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PUBLICATION 4 – MEETING LEARNING CHALLENGES IN PRODUCT DESIGN EDUCATION WITH AND THROUGH ADDITIVE MANUFACTURING

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PUBLICATION 1 – DESIGN ISSUES AND ORIENTATIONS IN ADDITIVE MANUFACTURING

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Design Issues and Orientations in Additive Manufacturing

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Abstract:
Journal articles, conferences, TV programs and books are now flooding the academic and popular market about Additive Manufacturing, commonly labelled 3D printing. In the context of Product Design, as distinct from engineering, this article focuses on design issues when considering using Additive Manufacturing technology in new product development or improving existing products. Offered is a detailed scope of the designer's role in product development using Additive Manufacturing technology. This is realised 1) as representations (prototypes, mock-ups, scaled-models etc.); 2) through manufacturing (tools, jigs, stencils etc.); and, 3) as manufactured artefacts (sunglasses, etc.). In addition, an approach to designing for both New Product Development and improvement of existing products is presented. This approach, called AICE (Adapt, Integrate, Compensate, Elongate), is elaborated and exemplified, giving guidelines to designers, engineers and makers. The article closes by reflecting on the implications of such an approach for the further development of design centred perspectives on Additive Manufacturing, moving dominant disciplinary discourses towards product design, development and analysis to complement the burgeoning attention to tools, material and production.

Keywords:
Rapid Prototyping, Rapid Tooling, Additive Manufacturing, 3D printing, Product Design, product development, Design issues, Design centred perspectives, design approach, AICE approach, iterative, loop-based model

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Title

1 Introduction

A focus on product design

Investigation of means and processes of production is the topic of many research articles in Additive Manufacturing (AM). In this one we take up a product design position in reflecting on how the design and design based perspectives on production processes may be characterised in AM. One key claim is that AM may reduce costs in print on demand or the scaling of production, but it does not help to make something cheaply if it is costly to develop. We argue that attention needs to be given to the design phases, elements and processes in AM. We further suggest that AM concerned with producing products may be better understood through a holistic view of the design issues present in and arising from the spread and linkage of elements in a product design development process.

Designerly ways of knowing (Cross, 2001) comes out of a need for design research to build on its own intellectual dicipline and practical nature, which is independent from other sciences and intellectual cultures. In what has been labelled a 'designerly approach' (Lawson, 2006), one of the key factors has been maintaining a holistic view on the product development process. This includes an understanding of the interrelations between production technologies, marketing, and culture. When designing for AM the possibilities enabled by these technologies allow designer-researchers to take the holistic approach even further. We unpack the different stages in the product development process and show examples on how design issues/opportunities will appear through the process chain. Further, we will introduce an approach, the AICE, to show how the possibilities emerging could be enhanced when AM is an option.

In this article we address this through focusing on matters of design in product development in AM in experimental lab and teaching contexts over the past decade or so. In a bottom-up and case based method of inquiry and critical reflection we have developed an abstracted set of guiding principles. These are encapsulated in what we have labelled the AICE Approach. The acronym stands for Adapt, Integrate, Compensate and Elongate, terms that are chosen to reflect designerly centred views on product development in AM.

Author

Outline

The first part of the article contextualises AM in a design view, with focus on designerly ways of knowing. Second, we present a key model for knowledge transformation that helps understand how AM and product design may be seen to influence once another. This is followed in the third section by a presentation of actual examples of developmental design work, including that of students. The AICE Approach then follows, after which the paper closes with a Discussion and Conclusion section.

2 Contextualising the inquiry

Throughout the 1990s and 2000s the movement of manufacturing of physical products to China and other places with low labour cost, led to an increase in non-physical production, services, interfaces etc. This was a natural development in a so-called post-industrialised society. However, this did not mean the end of product development, but services connected to a physical product would be developed and evolved long after the physical product had been introduced.[1]

Unpacking costs

The following subsection discusses AM cost of production in relation to conventional injection moulding, and seeks to open up from existing linear cost charts by taking a contextual view, emphasizing designerly approaches.

The obvious benefits in cost reduction when using tool-less production, like Additive Manufacturing (AM) (Hopkinson et al., 2006), has been the foundation for the massive interest for this technology and it has been embraced by engineers and politicians (President Obama, state of the Union 2013). Since the main reason for the cost reduction also relies heavily on a low number produced, Hopkinson et al. (2006) showed there would be a convergence point when the numbers of products would justify standard productions methods like injection moulding, it is also obvious that other cost in getting a product out to the market will be divided on a smaller number of units, leading to a significant impact on a product end price.[2]

There are three parameters that influence the production cost of an injection moulded product (Boothroyd et al., 2011). These are: 1) the price of the tool, 2) material of the product, and 3) matters of cost. We briefly summarise these as they have an impact on our wider argument below.

Firstly, the price of the tool is influenced by i) the number of cavities (how many products coming out of the tool after every shot), ii) the complexity of the tool (typically how many core or side pulls there are), and, iii) the size of the tool and the quality of the metal in it (if the tool is supposed to have a long life cycle, producing millions of products, the metal should be very durable, implying it is harder to finish and its cost is increased).

Secondly, designing for injection moulding (see curve B in Figure 1), the choice of material of the product, whether it is an affordable polymer, like a polypropylene that costs about 1$/kg, or a more expensive polymer like a polycarbonate that costs 4$/kg, starts to have an impact on the price when the numbers of products increases.

Thirdly, in production there are many ways to calculate the actual production cost (the cost of an injection moulding machine). One way is to set an hourly cost. The price of a larger machine capable to mould large or numerous parts will have higher hourly expenses than a smaller one. These three factors of course strongly influence each other, and the designer makes decisions that influence all the factors (Boothroyd et al., 2011). In addition to the production cost, there is a development cost (across the design process) and possibly some post-processing expenditures (Gibson et al., 2010).

In designing for Additive Manufacturing (see curve A in Figure 1), we may split the cost of a product into similar parameters. These are a design process, material cost, actual production cost and post-processing cost (Atzeni et al., 2010; Atzeni and Salmi, 2012). In this process, the product designer influences all these parameters. Uncritically following technical advice for a specific AM technology could lead to huge post-processing cost (Gibson et al., 2010). In the acts of making the designer needs to apply knowledge on site, for example, trapped powder or liquid from the building process needs to be easily removed.

As the curve in Figure 1 shows, when comparing all the cost involved - from developing the product, through production and to post-processing - the question of expenditure becomes slightly more complex.

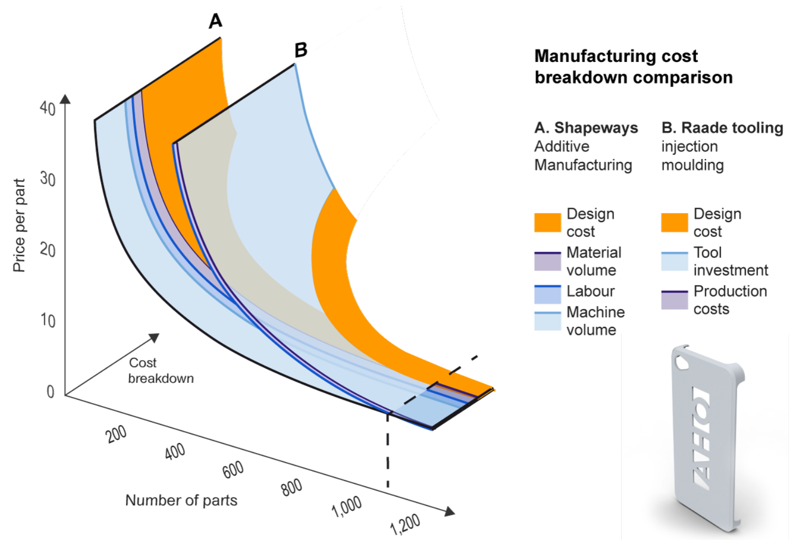

Figure 1 A comparison of production cost for injection moulding and an AM produced telephone casing. (William Kempton and Steinar Killi)

There have been previous attempts to show the cost of 3D printing parallel to conventional manufacturing. These only relate to specific production costs, with very little regard to the product development cost. Figure 1 was devised to illustrate as cost in depth on three axes: price per part, number of parts and cost breakdown. This is in contrast to a typical ‘break even’ linear chart. The three way diagram is related to a contextual view of product development where the designer’s actions, that is before, during and perhaps after the process, are part of production activity and not only a view on product development centred by cost breakdown.

Knowledge modelling and product development

Changes in product development and production may be framed in terms of knowledge production. One leading model for knowledge building in a company from a management perspective called SECI (Nonaka and Takeuchi, 1995), mapped relations between tacit and explicit knowledge and related these to a spiral of iterative processes of socialisation, modes of externalising knowledge, and ways it is combined and internalised.

Nonaka and Takeuchi’s model has evolved over the years and has been adapted by several others, very often in design branches like Service

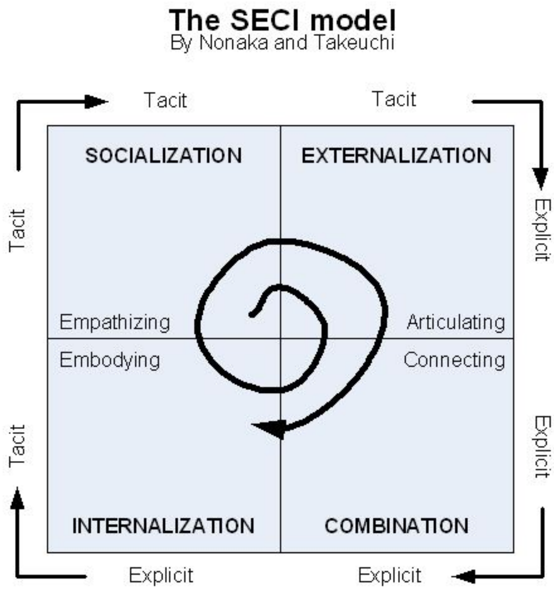

Figure 2 A version of the SECI mode. (Picture: courtesy of applitude.se)

Design (Gloppen, 2009). SECI is an acronym for Socialization, Externalization, Combination and Internalization (see Figure 2). Socialization labels the tacit to tacit knowledge transfer, very often through shared experiences. Externalization labels the transfer of tacit knowledge to explicit knowledge, formalising the knowledge. Combination labels the combining of different explicit knowledge, whether gathered externally or internally. Finally, Internalization labels the explicit to tacit knowledge transfer, creating the knowledge building loop. The core of the model is the exchange between tacit knowledge and explicit knowledge and how this exchange is effected.

Very often tacit knowledge is built through experience, and the resemblance with the distinction used in design between apprentice and master is often mentioned. From our point of view in Product Design, it is the interaction that happens between the tacit and explicit, in certain settings that is significant, and how this may lead to a fertile looping process. The model has been expanded to include knowledge assets and the shared context, called Ba (from the original Japanese).

This model has achieved almost paradigmatic status, but it has been challenged (Gourlay, 2003). Some of the critique has been the validation of the findings, how they have been achieved (through questionnaires) and how they have been analysed (Gourlay, 2003). It has been argued that "the SECI model is a process model and its validation must therefore require validation of processes, not simply 'content'" (Gourlay, 2003, p. 8).We would argue the model offers design an approach that may be adapted, modified, evolved and transformed around the tension between tacit and explicit knowledge. One interesting point here is the link to craftsmanship, and how crafting skills, or tacit knowledge, are the starting point and necessary intermediate points, in the spiral process.

For Product Design that is moving into working with AM, the model helps us to address the shift from tacit knowledge that is arrived at through processes of experimentation and innovation in design practice, and how we may unpack them analytically as their character and content become more known. To do so, however, we need to be able to better situate and analyse AM in the context of Socialization, Externalization, Internalization and Combination as mentioned above.

A Process Design Model for AM in Product Design

In order to contextualise this iterative approach as a design-centred one to AM, we include a Process Design Model for AM in Product Design that has come out of the work of Steinar Killi (2013). It is important that this way of working with AM is understood as reflexively design centred. The Process Design Model for AM in Product Design was developed prior to the AICE Model presented later in the article. This model offers ways to incorporate AM as a visual catalyst for facilitating decision-making across several diciplines.

Value co-production

Another perspective regarding production, from a management level, is value co-production or simultaneous production and consumption. These terms emerged as theoretical models in the 1990s, although the concepts of simultaneous production and consumption are far from novel (Ramirez, 1999). In the manufacture of physical products, the sequence is very often that the product is produced, sold and finally consumed.

On the one hand, this has changed to a development path in which, for instance with cars that the products today have a customer before being produced. On the other hand, the bulk of physical products are produced

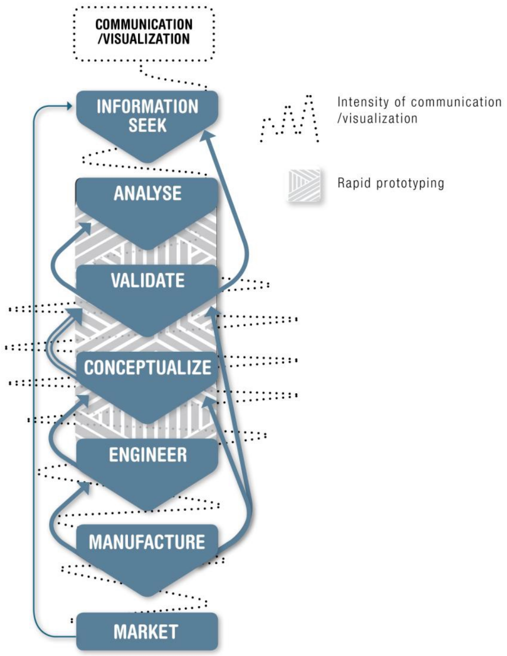

Figure 3 A Process Design Model for AM in Product Design, with visualisation and communication design elements. Based on the Capjon-Øxseth-Killi approach to a design process. Rapid prototyping is used extensively through the process, as a visual catalyst in multidisciplinary decision-making. (Visualisation: Emilie Strømmen Olsen and Steinar Killi).

and then shipped of to a retailer that has made an estimate of how many it would be possible to sell. Services, however, are very often sold before they produced, as is frequently so in the nature of the service.

From the point of view of the product designer and researcher located in AM, the term simultaneous production and consumption are more valid. They apply to the AICE approach in that they allow us to consider production in terms of delivery that is just in time, or just in need.
We see that some actions are purely consumption and they find their direct counterpart in production. For instance, a band records an album and a customer listens to it. However, there are also areas were the production and consumption happen simultaneously, such as Karaoke (Ebare, 2004).

Parallels between the continuums described above, for the production and consumption of music, and Direct Digital Manufacturing (DDM) can easily be seen in relation to AM. There is already a blurred image of producers (amateurs and professionals who design artefacts and share them on the net, for instance at thingiverse.com) and consumers (who download files from for instance Thingiverse and produce artefacts for personal use on their home 3D printer).

In the next main section we present our own Product design practice in developing AM products and explicit knowledge through experimentation, teaching and research.

3 Design objects in product development: from prototypes to end-user artefacts

Below we categorise output areas of Additive Manufacturing (AM) from a design perspective, and principally that of Product Design. We outline three separate categories within which we locate examples of actual developmental product design work. The first set of examples covers those defined according to their ability to act as representations. Secondly, there are ones defined through their role for manufacturing. Thirdly, we cover those defined as manufactured objects.

As representations

Additive Manufacturing has a long history of making prototypes. Once labelled Rapid Prototyping, it has in recent decades allowed designers to quickly advance design concepts into functional, visual or scaled models and prototypes. Today a plethora of remote and local 3D printing services and products exist. They provide its users with 3D objects from digital inputs, while fitting the users constraints of time and cost. They technology is becoming an integrated part of many creative practices, such as architectural and industrial design practise. It is found in city planning departments (at Oslo PBE it is used for visualizing urban planning), media outlets (such as NRK in Norway) as well as in many educative facilities that are involved in design. What purpose do Additive Manufacturing in these areas serve, and why do they physically prototype their ideas?

Creating models and prototypes is a core practise in many design disciplines, and is facilitated in many different ways: paper prototyping, software prototyping, mock-ups etc. Prototypes are themselves also classified in relation to their complexity, precision, or purpose, all depending on the context of its use (Beaudouin-Lafon and Mackay, 2003).

Figure 4 Kobra oral retractor for Saga Dental AS. (Image courtesy Hanne Morstad, Danee Feng, Frøye Thue and August Skaara)

In the context of product development it serves many different purposes. It can boost the ideation process by providing physical evidence of an idea. It might facilitate the elimination of faults and errors in a given design. It can also aid the creative and demonstrative capabilities of a design concept, as manifested through the MIT credo "Demo or Die" (Schrage, 2000). We can say that these scaled, visual or functional prototypes act as representations of a design. They become mediators of shape, composition or ergonomic fit. New radical design proposals may more simply be approved or rejected because of the existence of a physical prototype.

The use of AM technologies in the prototyping process has many advantages. The digital blueprint, often a product of CAD, is physically reproduced and aids the decision-making process of the involved stakeholders. As the prototypes are precise, they allow for highly iterative processes. Figure 4 illustrates how a 3D printed prototype of a dental retractor for Saga Dental fits a potential user. The design, titled 'cobra', had a pronounced helical shape, and relied on a physical mock-up to be properly evaluated. The 3D printed mock-up allowed the designers to evaluate the feasibility of the overall design, and improving faults in order to eliminate issues that might occur further down the road.

Author

Figure 5 Silver engagement ring made through lost wax casting process (Design by William Kempton, picture by Maria Karlsen)

For manufacturing

Apart from acting as representations of design ideas, AM might indirectly be of aid in both design and material production. Increasingly AM is being used in different manufacturing processes, as tools or other improvements to improve manufacturing operations (Hiemenz, 2011), as jigs in the assembly line, or even as moulds for mass customised artefacts. In fact, tooling is already a major market in Additive Manufacturing (Wohlers, 2013). The tools, either directly or indirectly involved in product manufacture, are often made in small amounts, and have a complex shape because of its specific application. They harness the unique capabilities of AM technologies, which include Lead time reduction, improved functionality, and increased ability to customise (Cotteleer et al., 2014).

In jewellery design, the ability to create physical prototypes in wax for instance using Solidscape 3D printers, means a quick and precise way of creating patterns for moulds utilizing a lost wax casting process. A complex ring design, seen in Figure 5, can only feasibly be made this way. It is an engagement ring, and is specifically designed for this purpose, containing highly contextual symbolism. The ring harnesses both customisable and enhanced aspects of AM technology to a high extent (Killi, 2013).

Figure 6 illustrates how a company logo can be sprayed on a surface with a 3D printed stencil. Stencils are often made on a 2D surface by laser- or CNC knife-cutting, resulting in necessary bridges between isolated

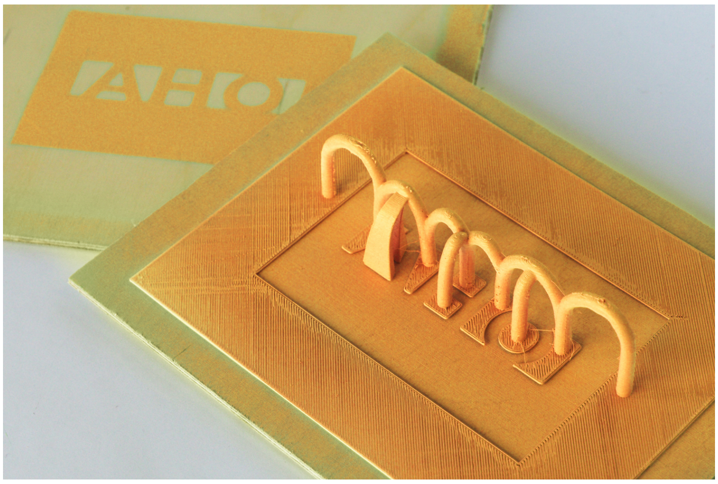

Figure 6 AHO logo stencil. (Designed by William Kempton, photo by Maria Karlsen)

elements that are visible on the painted surface. Created on an Ultimaker desktop 3D printer, the 3D stencil is able to place the bridges without interfering with the sprayed surface.

As mentioned in the introduction, a major barrier in conventional tool-based manufacturing is found in the cost of creating a mould. A designer working with a specific material such as 3D veneer, might need to do make material samples in order to understand a specific form-making quality. By utilizing for instance SLS technology and a durable PA-12 nylon material, moulds can be created to aid the designer to perform these material experiments. Figure 7 illustrates how such a mould might look like. The mould is capable of creating multiple samples for prototyping other materials, such as veneer or aluminium.

As manufactured artefacts

The categorisation of AM products that has received most attention in recent AM research as well as through media (Markillie, 2012), is the possibility of creating products that are directly and specifically made for use by end-users. As opposed to creating objects as representations or for manufacturing, here AM technology substitutes conventional manufacturing such as moulding, extrusion or forming. This already has a big influence of leveraging economies of scale such as in aerospace, where parts and objects can be manufactured directly, drastically reducing the

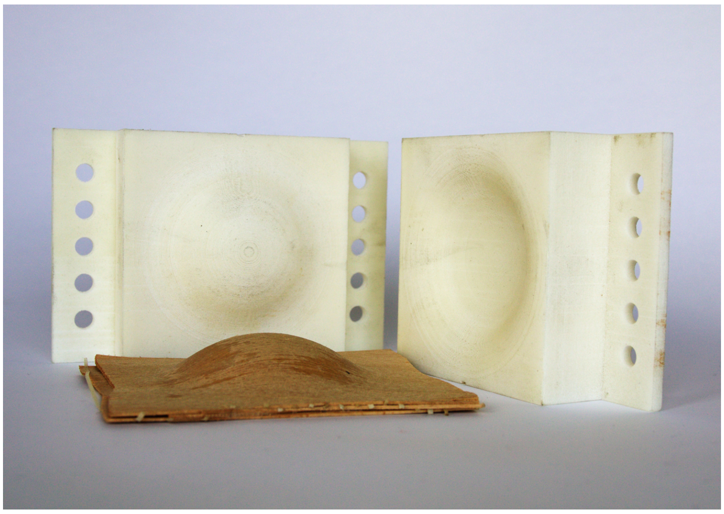

Figure 7 Wooden Veneer mould. (Designed by William Kempton, photo by Maria Karlsen)

buy-to-fly ratio, the ability to create functioning objects with less use of raw material (Reeves, 2009).

There are many factors to consider when determining the use of AM for production. Firstly, there are many different processes that make up Additive Manufacturing. They involve powder bed fusion, material extrusion, photo-polymerisation, sheet lamination and directed energy deposition. These technologies can be categorised from the baseline technology they employ (laser, heat extrusion, etc.), or by the raw material that is inputted to them. However, this might create odd combinations of processes (Gibson et al., 2010, p. 27).

Another more holistic approach is to identify different product domains based on the factors of Customisation, Complexity and Volume (Conner et al., 2014). Different variations of these factors, such as low volume and high complexity, make it possible do define products that can be mass customisable, artisanal, or by harnessing the complex structures that the processes may be able to provide. Furthermore, specific areas that are of interest within complexity include parts consolidation and multiple assemblies manufactured as one (Hopkinson et al., 2006).

The example in Figure 8, although produced in a low quantity on a desktop 3D printer, can be said to be a highly customised artisanal product. The product, an earpiece for holding several pens, was to be

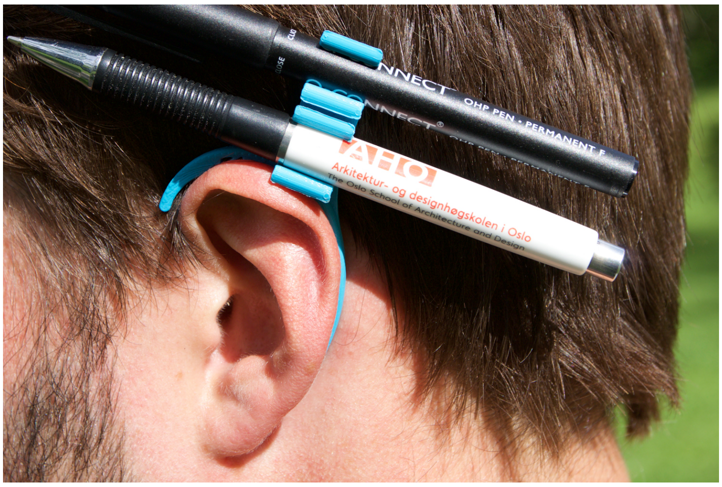

Figure 8 Pen holder for the ear. (Design and image by William Kempton)

custom fitted to the subject's ear. In addition, it allows the user to decide the amount of pens attached, as well as their diameter. The design process was highly iterative, using the same AM technology to create the prototypes as the end-use item.

Figure 9 illustrates a pair of sunglasses inspired by Inuit sun goggles. It has consolidated its product features into one single SLS part. There are no hinges, as it is made to fit a single person. Neither are there optics, as an open slot provides the viewer with a smaller viewing aperture to limit sun exposure. The design of the product is highly customised, as it is digitally modelled around a 3D scan of the wearer's face.

Figure 10 shows a part of a large architectural structure where crucial parts of an artefact have been manufactured with the SLS process. These parts, the joints, connect a series of extruded aluminium tubes to form a large structure. As each joint was deliberately designed to be different, there was no other way than to produce the joints by AM, numbering 96 in all. This example explains how a single part can be a part of a wider assembly.

The characterisation of the different ranges of use made in this article goes some way to explain ways in which AM technologies can influence the process of design. It has primarily been a useful tool for creating representations in a design process. The technology can be used to make tools, jigs or moulds, harnessing its unique capabilities for manufacturing.

Figure 9 Inuit-inspired contemporary sun goggles. (Designed by William Kempton)

Figure 10 Joint for a architectural installation intended as an entrance gate to a science fair in Oslo. (Design and photo by Espen Bærheim)

Increasingly, it is proposed as a method for creating objects as manufactured. Many of the examples in the category we manufactured have in common that they saw various iterations through the same processes as were ultimately used. That pattern that arises is that they are inevitably all prototypes in themselves.

However, we see a need to reach beyond such an illustrative categorisation. In the next section we present an approach for designing for 3D printing that encapsulates both our extended practice and our analytical research capacities in the development of a model to abstract the design processes and relations.

In the overall section above we have presented design exemplars that illustrate a designerly design process working New Product Development to AM. This raised issues concerned with adaption of design methods, the integration of levels of functionality (e.g. shape, process), ways of compensating for the replacement a manufacturing product process with tools relating to AM production processes (e.g. adding colour), and the elongation of a process of rigidity and fixity to the expansion of a continuous and facilitative design process.

It is these four main changes that we now take up in presenting the AICE Approach to designing for 3D printing and for understanding a design view on New Product Development in the domain of AM.

4 AICE: an approach to designing for 3D printing

Considering the importance of a designerly approach (Cross, 2001), as depicted in Figure 11 and how the Additive Manufacturing technology could play a role in so many ways during and before product development, it is helpful to further unpack the developmental approach to the design process. The following material was mostly developed in a doctoral project entitled *Designing for Additive Manufacturing: Perspectives from Product Design* (Killi, 2013).

Background to the AICE Approach

There are literary hundreds of different design methods (Dubberly, 2004): analytical, creative or in the shape of design manuals defined by a brand or company (Cross, 1993). There are several white papers claiming to educate designers for specific Additive Manufacturing technology (Comb, 2012), but they are typically in the form of a user manual to how shapes and details should be to optimize the benefits of the specific technology. An example is different wall thicknesses and overhang, and this is well

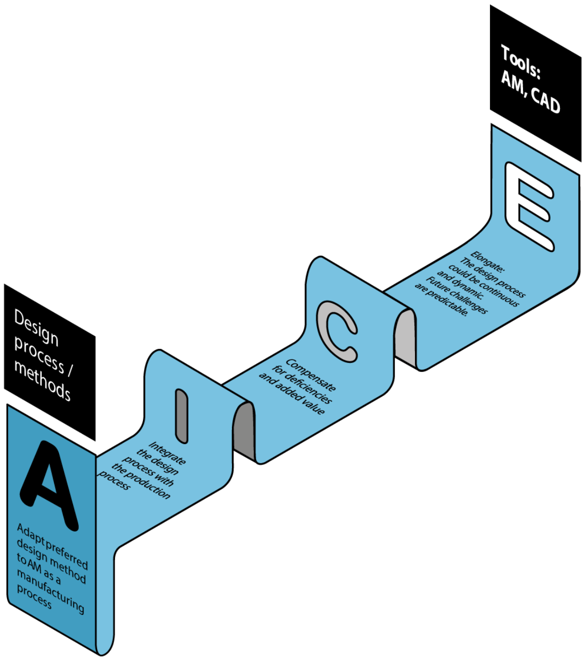

Figure 11 The AICE Approach. (Visualisation Emilie Strømmen Olsen, Maria Karlsen and Steinar Killi)

suited for this technology, in opposite to regular injection moulding. Further, negative implications like placements in building envelope, challenges with support structures and possible delamination are well catered for. In many ways these views could be labelled design rules (Comb, 2012). Technical issues like those covered in a typical whitepaper from a manufacturer are of great interest but what is needed is a synthetic analytical model that incorporates creative methods adjusted to the possibilities AM technology provides. So instead of just focusing on design rules, the AICE Approach focuses on the possibilities the technology may open out, and how we might pursue these possibilities methodologically.

AICE: summary

AICE is an acronym for Adapt, Integrate, Compensate and Elongate. The method seeks to bridge the possibilities that lie in AM technology from a design perspective (Killi, 2013). The components of AICE may be described as follows:

Title

ADAPT: A general rule is that products should be made closer to the end user, adapting to its surroundings, using off the shelf items when appropriate. During the research phase some issues may be clarified:
1. *Enduring*: Will the end product serve as test product and be produced conventionally if successful? If so, should the design be adaptable for this without undergoing a total redesign?
2. *Marking*: Will the end product be a one of a kind, either customised or by some sort of an algorithm? If so, the design should be adaptable to shelf products, i.e. batteries and light bulbs for a flashlight.
3. *Changing*: Usually a designer adapts the product to a specific manufacturing process. The same goes for AM, benefits of processes are weighed up against disadvantages, changes in design could be necessary to perform in order to use a certain process.

INTEGRATE: Functionality should be integrated to a much higher extent in the shape, whether it is strengthening the structure, using the manufacturing process actively (different elasticity on shoe sole by using different laser power, anisotropy, etc.). Mechanical strength could be optimized and be conformal to the shape. Issues arising include:
1. *Altering*: the shape itself could increase stiffness/strength, using double curved surfaces, nonlinear rib-patterns, hollowing volumes and trapping unprocessed material.
2. *Varying*: Using different thickness.
3. *Allocating*: space for stiffer material, like steel rods/plates.
4. *Designing*: different mechanical values into the production process, using for instance different processing parameters (Hopkinson et al., 2006).
5. *Changing*: mechanical properties linearly or non linearly, both functionality in music instruments (Killi, 2010), and aesthetically (jewellery, transparency) could be integrated directly in the design.
6. *Integrating*: when integrating all/much into one design, local fatigue and access to spare parts have to be addressed (Hague et al., 2003).
7. *Embedding*: identity or brand into the shape itself, could enhance the free form fabrication effect, and even compensate for the lack of materials/finish.

COMPENSATE: Deficiency in quality due to fewer materials, varying accuracy, technology dependency and software limitations needs to be compensated for, by adding materials, for instance, for strength locally, post processing techniques (metalizing, lacquering and partly moulding) for increased surface quality, and in choosing the right AM technology for the right product. This leads to the following:

1. *Tweaking*: If the end product needs visual qualities (finish, colours, translucency, etc.), the number of AM processes is fewer and may result in strength issues, or, if these mechanical demands are dominant, some kind of post-processing will be necessary.
2. *Substituting*: If the processes are not fully understood and compensated for in the design, secondary and less fulfilling manufacturing methods have to be chosen. The Norwegian achievement award in engineering 2006-2010 pushed the technology to the edge. The award designed for 2011-2015 turned out to be impossible to manufacture the same way as the previous award. Several options were evaluated: Lost wax casting, metal plating of SLS sintered polyamide and other materials that could be used in the AM process. The choice fell on the latter solution. A batch of a copper-polyamide mixture was made specifically for the occasion. This composite had existed before, but never achieved any commercial success. This material solved issues relating to the aesthetical, haptics and metallic look, weight and touch, that were vital for this project. This case shows the importance of adapting the design to the manufacturing process. Not everything is yet possible, but this instance also shows the versatility in the technology, and the possibility to compensate for deficiencies in the process.
3. *Tuning*: All processes have accuracy issues and problems with repeatability (Gibson et al., 2010). There are no tools to do changes or adjustments: either the digital file has to be tuned and/or the process has to be tuned. Problems with accuracy and repeatability may be compensated by a design that is flexible, allowing a shift in product quality. Products with demands of accuracy should be designed to compensate for this.
4. *Boosting*: Production issues differ for the different AM technologies (Gibson et al., 2010). For SLS its repeatability, process parameters (temperature, age of material, placement in production chamber, etc.) that matter. This may lead to large deviances in for instance mechanical properties. Creativity is important. The need to compensate either for process deficiency or for context (amount, users, etc.) may serve as a creativity boost.
5. *Sustaining*: Many, or most, of the AM processes today are not sustainable: this refers to the process itself, the materials or the lack of possibility of recycling parts or materials used during the process such as support (SLA, FDM, OBJET) or over recycled powder (SLS). In the future, one could see the possibility of recycling parts, to compensate for

some of the footprints from this process, and close mixing of materials should be avoided.
6. *Benefitting*: A deficiency in a process could be used as a benefit. Steps from different layers in hearing aids provide a more comfortable placement in the user's ear, avoiding an unpleasant vacuum due to the perfect fit. For example, products made in laser form, a two step process resulting in a steel-bronze alloy, will have a porosity that could be used for self-lubricating parts, resembling those made conventionally with hot or cold isostatic pressure (HIP or CIP); different shades of colour.

ELONGATE: The product frame should be stretched, literally by using the concept form-elasticity, 3D branding and exploring niches extensively. A large number of products, especially typical brand products (cars, bikes, clothes, jewellery), are designed within a frame: a Toyota should look like a Toyota (Karjalainen, 2007). That means that the product contains design elements, big and small, that make the product recognizable, although it is a new model. These elements are not exact replicas from year to year, model to model; they are often stretched but recognizable. The term form-elasticity is one of the strongest design tools we have when designing for AM. A number of observations can thus be made:

1. *Modularising*: Designing for mass production, to some extent, has been all about making choices, choosing a concept, a main shape, details, finish and colours. The goals are to tune these into a product that a mass of prospective customers are expected to like and purchase. Designing for mass customisation has, to a great extent been all about splitting a design up into modules, and letting the customer make the choices (Killi, 2007). This could lead to numerous unique combinations (BMW World 2011), although the customer and others will still recognize both brand and model and probably not interpret the product as being very unique or "personalized". All parts of the product are still "tool-based", meaning that each module is made in a huge quantity and it is the assembly of it that is unique. Letting the whole or some of the products be produced without tools, with AM the shape could be truly unique, personalized, bespoke etc.
2. *Stretching*: To use the form elasticity when designing unique products, a template should be made. A main shape is developed, but the design elements are possible to change for every product. The designer needs to control the whole boundary of possibilities, allowing the user to actually stretch the concept. Elongated design strategies could address and anticipate challenges that are still unknown and/or unmet, instead of addressing a common denominator. As it follows through, this may lead to

Figure 12a and b. Casing for a Samsung Note, produced using SLS, promoted and sold online. (Design and pictures: Rasmus Agerup)

a design that stretches into niches that so far have not been commercially interesting.
3. *Shaping*: Since the materials available have limited aesthetical values, the shape or form of a product is even more important. This is especially so for products with a large visual value, the plasticity and versatility of the AM process could be stretched almost dynamically.
4. *Versioning*: The design process should be elongated beyond the production of the first product, much like a web based newspaper where the articles are continuously updated; improvements and changes should be possible to conduct. The number of versions, in an extreme case, may be as many as the number of products, looping between the designs and manufacturing each time a product is made.

Reflecting on the AICE Approach

The AICE Approach was introduced to 2nd year bachelor degree students in industrial design. Their task was to develop a cell phone casing that could be produced using selective Laser Sintering (SLS), the result was promoted and sold over a two week period through a webpage (fabrikkaho.no). One of the casings are shown in Figures 12 a and b, in the form of casings for an HTC model mobile phone. Referring to the AICE Approach, the project was *enduring* in the sense that the iterations and the end product are connected, and continuously evolving to the desired production method (in this case SLS).

Figure 12b shows part of the design process, different possibilities for functionality, personalisation and structural elements were investigated, adapting standard design methods to the new possibilities AM provided. Rasmus Agerup, the designer, also integrated the back support for viewing pictures/movies with room for access card. He also removed the original back plate of the phone, *integrating* the cover and the phone. In *compensating* for in-accuracies, he developed patterns to decrease the stiffness of the structure, making the cover able to adjust (stretch) to the phone even when a produced casing came out slightly off on measurements. By removing plastic and creating an appealing pattern he made the post-processing easier. Finally, making the cover with adjustable features he opened for an elongated life span, when Samsung would launch new models of their smartphones.

During a design process, the designer will typically arrive at a point where qualified decisions need to be made. The brief example with the phone casing, as pictured in Figure 12, exemplifies some typical design challenges and possibilities, where knowledge of the AICE Approach might be of help. As the example also shows, the approach needs to be adapted according the task, as well as for the designer himself. This is why we label AICE as an approach and not a methodology.

5 Discussion and Conclusion

When initiating a product development process, whether for new or existing products, there are different mindsets available for approaching the task. Krippendorf (2007) suggest three modes; 1) problem based, 2) solution driven, and 3) possibility driven. Due to the nature of AM technology, all three modes could work as a point of departure, similar to that of a standard mass production paradigm. However, what AM contributes is a motivation to navigate through all these modes simultaneously; solving a problem generates several solutions that could be realized. Further, through the process, possibilities will emerge that could also be realized without either prolonging the design process or increasing the cost.

It is important to emphasize that AICE should be seen as an flexible approach. Prospective users should fill in methods to adapt it, updating practical implications due to technological advancements, and not see it as a rigorous or structural tool only that cannot be used in designerly ways. The AICE approach presented is not likely to be and perhaps should not ever be finalized. In contrast, it should be tailored and adjusted to encompass users' needs and wishes and suit the ways designers work, but also be oriented towards the development of AM technology itself. New design rules for new technologies will appear: some of the practical parts of the approach will necessarily change, but hopefully the AICE Approach could be developed to be a tool to seek out the possibilities this technology offers in product development.

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[1] Examples here are iTunes for Apple or Apps for smart phones, you need some kind of physical platform, but then new services could be developed, creating new revenue without a trace of physical products. This would also mean that without any services connected to a platform (the physical object), it would soon become obsolete. A famous example of this is the video-tape industry in the 1980s; just one system survived, the VHS, and those with the other platforms were left with an obsolete equipment (Owen, 2005). From a management point of view, finding the balance of physical products and services linked to it is crucial. The immaterial services could both in theory, and in practice, evolve daily. At some point the new services designed would need a new platform, but there could go years before that happened, example here are game consoles, like Playstation or Nintendo. This will also lead to a design process were the "product" (a smart phone app for instance) are never finished. There will be an elongated design process; revenue could be generated parallel with the design process.

[2] For example, a cell phone cover costs 1$ to produce using Selective Laser Sintering (SLS), but if a designer spent 10 hours designing it and a worker spent 10 minutes cleaning it, there will be a different calculation for an end price compared with ordinary mass-production.

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Chapter 2

A Design Sociotechnical Making of 3D Printing

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2.1 Introduction

2.1.1 Disciplinary Boundaries and Claims to 3D Printing

As 3D printing is moving toward the attention of wide-ranging societal context and spaces, it is taking on an increasing amount of roles and potentialities [25]. While initially seen as a developmental tool for designers, architects, and engineers, digital fabrication (with 3D printing as a lead indicator) is moving outside of these professional practices. Its recent claims span from a facilitator of distributed and personalized material production [5] to future challenges for intellectual property [7]. It is seen as a tool for self-motivated makers [1] to turn digital information into physical reality and as a platform for free, open-source innovation [42]. While the

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development of digital fabrication and 3D printing has been ongoing since the 1980s [44], the popular and academic interest in this emerging technology can be demarcated by the expiry of major 3D printing patents in 2009 [6].

In engineering-driven disciplines [13, 15, 17], much emphasis is put on a particular avenue known as additive manufacturing (AM), which can be seen as advancing the concept of rapid prototyping (RP) in a mass-manufacturing paradigm. RP has since the early days of 3D printing facilitated the rapid making of prototypes for product designers, engineers, and architects. Here, 3D printing in the context of design is situated close to developmental methodologies, typically as a means of confirming ergonomic, visual, or mechanical considerations within a design space [33].

Whereas RP is often linked to developmental methodologies, the logic of additive material production moves us closer to the nature of the fabrication process. As opposed to subtractive material production, such as vacuum forming, injection molding, or die casting, additive fabrication implies the accumulation of matter into layers and building blocks, thereby evoking an idea of fabrication inspired by nature [31]. In relation to the potentials of AM in a consumer-oriented version of design, it gives the ability to make complex, customized, and multimaterial artefacts, while still being "cost effective" and "giving the potential for much greater customer satisfaction" [17].

As opposed to mere consumption-oriented digital fabrication, Gershenfeld (2008) relates these technologies closer to personal, developmental use [14]. Gershenfeld remarks on how having access to 3D printers, laser cutters, and other manufacturing tools creates a "physical notion of literacy." In this sense, Gershenfeld likens literacy to the ability to express oneself through whatever means are available.

2.1.2 Introducing a Sociotechnical Perspective to 3D Printing

At its core, this book chapter analyzes the emerging social practice, mediation, and knowledge that are being carried through the development of the 3D printer. This argument is based on a social constructivist idea of technological development as being constructed through social intervention. I align my arguments to the critical theories of science and technology studies (STS), such as those by Feenberg, Ihde, and Bijker, in order to contextualize man-made technological artifacts into their natural, technical, and social environments. This argument is facilitated through a set of theoretical concepts, such as the relevant social groups that interact with and mediate the use of technological artifacts through a technological frame. This argument of sociotechnical interplay allows my discussion to center on the production of knowledge, as opposed to the decontextualized technological production of artifacts.

By incorporating theories and discussions from sociotechnical studies [4, 11, 18], I take on an ontological view of technological development as being undeterministic. Such a view implies that nonintentional use and technological adoption in the “real world” influence the way technology is constructed. This view can be seen in contrast to linear, deterministic views of technological development that imply that it is decontextualized from its users and placement in societal contexts.

2.1.2.1 Sociotechnical development from a design perspective

Through the disciplinary views and uses of digital fabrication that I will discuss throughout this chapter, claims are being made that reposition boundaries between digital information and physical material making. The unpacking of disciplinary perspectives of digital fabrication is also relevant to both design research and practice, such as in human–computer interaction (HCI), whose concern with digital fabrication involves developing tools that support making processes [24]. As a technology that facilitates the making of physical artifacts, digital fabrication’s influence on product-oriented design disciplines is wide ranging. When considering product design as an iterative “problem solving” process that involves stages of trial and error [38], digital fabrication allows designers to prototype and imitate abstract design concepts into concrete material visions, both quickly and efficiently.

Although digital fabrication is mostly associated with the production of plastic, metallic, or ceramic goods for conceptualizing and making artifacts, it is also possible to fabricate with novel materials, such as edible food. The 3D-printed gingerbread house, shown in Fig. 2.1, seeks to illustrate one of many potential engagements with 3D printing, which brings into question a view of digital fabrication, specifically that of 3D printing, as a platform for making "useful" artifacts. The digitally fabricated gingerbread house problematizes new avenues for engagement with novel materials and digital fabrication that are found on the periphery of conventional, consumer-oriented design.

Figure 2.1 Novel material approaches to 3D printing through the making of a digitally fabricated gingerbread house. Photo and design: William Kempton.

Through contexts and sociotechnological perspectives that are built up in a way that is relevant for design, I ask, "What are the perspectives and disciplinary claims that allow us to understand a contemporary view of 3D printing?"

2.1.3 Outline

The chapter is separated into seven sections. The first section introduces views of design and multidisciplinary views on digital fabrication. In the second section I elaborate on the concept of sociotechnical development as an undetermined process, to be played out by several relevant social groups. This is then contextualized within my discussions of digital fabrication and theories of nonlinear technological development. The argument for a socially constructed perspective of digital fabrication and making is then furthered through the introduction of several disciplinary perspectives. In Sections 2.3, 2.4, 2.5, and 2.6, I describe the development of 3D printing from the respective perspectives of 3D printer inventors, business managers, designers, and layperson makers. In Section 2.7 I discuss and summarize my conclusions.

2.2 Socially Constructed Technologies and 3D Printing

2.2.1 The Relevance of Social Groups

The engagement of people has an influence on the shaping of technological artifacts. This is particularly evident in the case of the development of technologies for home video entertainment. Since the introduction of the first video cassette recorder (VCR), followed through with the analog Video Home System (VHS) and Betamax format, and eventually Blu-ray versus HD-DVD, a series of format wars have occurred, sparked by social intervention. The Hollywood studios, the technology manufacturers, the government, and the users themselves can be seen as relevant social groups that all play a role in the shaping of domestic video technology.

In his monograph on the development of VCRs, Greenberg (2010) also emphasizes the importance of looking in between the "traditional protagonists" of sociotechnical development [16]. In the case of VCRs, Greenberg points to the way new technologies are mediated and the emerging contexts that surround it, what he describes as the "layers of mediation [which] help to package, distribute, and sell the product" [16]. In the early days of the VCR, small business owners mediated new technologies to their customers by renting out video cassettes and players. Although VCRs were initially intended for time-shifting (recording TV series while away), they also made it easier for the relevant social group of VCR owners to make their own movies and record footage using VHS-compatible video recorders. Early adopters of these technologies could record, transfer, and edit family videos and amateur footage at home, without having to go through the elaborate process of developing 8mm and 16mm film.

2.2.2 From Video Production to Material Production

The sociotechnical development of video entertainment changed many of the existing patterns of video consumption. Before the development of VCRs, owners of TVs were usually confined to the watching of direct TV broadcast at a specific time allotted by the broadcasters. Popular TV shows would be sent during prime time, accompanied by advertisements, which generated revenue for the broadcasters. Through new innovations in video technology, the VCR allowed users to materialize their own content by time-shifting their preferred TV shows, possibly skipping adverts, as well as video-recording and editing their own movies. These can be seen as acts of materializing content. Much in the same way, the concept of 3D printing involves actors materializing physical content by additive means.

2.2.3 Technologies for Additive Making

Figure 2.2 shows two design students in the act of producing material artifacts in clay and plastic using desktop 3D printers. While their attention seems to be focused on the desktop fabricators' remarkable ability to reproduce their design, the proximity of the computer in the background hints at the important presence of digital applications for facilitating the "making" of their design. The landscape of 3D printing, from large industrial processes to small, desktop fabricators is in fact made up of layers of technological systems. Engineered mechanisms such as high-precision stepper motors provide precise motion, while strings of computational code connect and put these mechanisms into useful motion. In a decontextualized view on technology, the sum of all these elements can be viewed as affordances that can be optimized and evaluated in terms of efficiency. In such a quantitative portrayal of technology, the success or failure of the various 3D printing technologies would be a simple matter of evaluating the technology with the highest output, quality, and affordability.

However, from a situated, socially aware point of view, the technological development of tools can be viewed as an undetermined entity, as it is always subject to use and manipulation by nature and society. As with any technology that exists or has ever existed, from hammers and nails to online sharing platforms, social interaction shapes the uses, contexts, and discourses on technology. This consequently leads technology onto unlinear tracks of development. In the case of digital fabrication and 3D printing, designers, engineers, makers, educators, and business developers contribute to different discourses on the same basic devices. While the current desktop 3D printers, currently capable of producing small-scale plastic artifacts, may be critiqued by professional actors within quality assurance and operations management as being of inferior quality to other industrial processes, their availability to an audience outside of organized product development is opening up paths for new entrepreneurial endeavors.

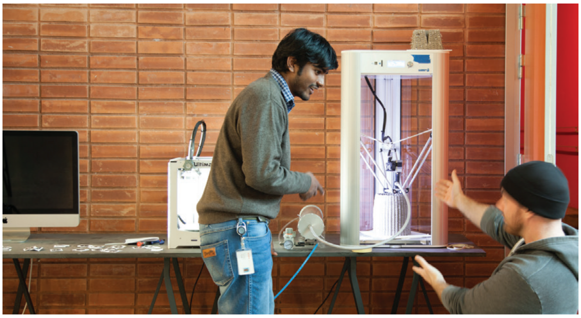


Figure 2.2 Design students involved in materializing clay artifacts with a desktop 3D printer. The computer in the background hints at the complex assemblage of technologies that 3D printing relies on. Photo: William Kempton.

2.2.4 Critical Theories and Studies of Technology

In his critical theory of technology, Feenberg and Callon (2010) analyze the construction of technology on two levels [11]. Firstly, technology is decontextualized from its users, situations, and things into basic technological affordances. Secondly, it is recontextualized into natural, technical, and social environments, which is essential in order to understand the real-life world of technology. Feenberg and Callon introduce the concept of technical code to discuss the rule under which technologies are developed in social contexts, with biases reflecting the unequal distribution of social power [14]. As technologies evolve, new social groups challenge the technical code through new designs. Such a case is famously described by Bijker (1997) in relation to the development of the bicycle at the turn of the nineteenth century, which fragmented into opposing bicycle designs used by different relevant social groups [4]. While the larger-wheeled bicycles, such as velocipedes, appealed to a completive social group, the smaller-wheeled safety bike was perceived as more utilitarian. Only after the invention of the rubber tire did the opposing social groups converge on a similar technological track by using smaller wheels. The story of the development of the bicycle serves as a well-suited example in explaining undeterminism as a hermeneutical track. One can interpret the inevitable stabilization of the now archetypal bicycle design as inevitable, due to functional improvements in the making of rubber tires. However, as is central to Feenberg and Callon's perspective, the concept of function has no use for meaning, as "the concept of 'function' strips technology bare of social contexts, focusing engineers and managers on just what they need to know to do their job" [11].

2.2.5 Unpacking the Views of 3D Printing

When the first additive digital fabrication technologies were developed in the 1980s, they were primarily used by engineers and designers for verifying ideas and prototypes in a product development process. The use of the term "rapid prototyping" gives an impression of the limited scope of use at the time. However, as the maturation of cheap, powerful electronics converged with the liberation of certain 3D printing patents [6], the landscape of 3D printing rapidly opened up to new fields of users and social contexts.

From a social sciences perspective, Birtchnell and Urry (2016) discuss 3D printing from the perspective of increasing globalization and mobility and how it might really reconfigure the existing patterns of production, distribution, and consumption. The authors point to great social-technical potentials of 3D printing, such as its ability to tailor for individual needs and use, which in turn might alter the current consumptive paradigms we live by [5]. Arguably these emerging technologies have the potential to change, or at least challenge, the current paradigms of consumption. However, I place the conceptualization of these changes in the hands of emerging design practice.

Broken down to its bare technological affordances, 3D printing has arguably not changed much for design practitioners since its original inception. Technologies that deliver high-quality artifacts, such as selective laser sintering (SLS) (see Appendix) and stereolithography (see Appendix), were in fact the principal technologies to be developed. What has changed significantly is the way the technology is approached by its relevant social groups. In the early years of 3D printing, the complex equipment and necessary expert knowledge demanded dedicated third-party service providers and large corporations. Designers and engineers would send 3D blueprints to third parties and have them sent back as tangible artifacts, allowing them to verify technical or aesthetical concepts at critical moments.

The process of making with 3D printing is today increasingly weaved into the initially conceptual, value-making stages of design. This has also made it simpler for smaller, less capital-heavy organizations, such as local maker spaces and design collaboratives, to partake in and use digital fabrication. New ideas, concepts, and services related to digital fabrication emerge, from novel household products to interactive robots that stimulate the presence for sick schoolchildren [29] and distributed manufacturing networks such as 3Dhubs.com.

2.2.6 Socially Constructed Perspectives of Additive Making

Following up on my initial argument for constructing a technological perspective that is aware of social practices, I will now turn to a contextualization of what 3D printing means from the perspectives of a set of relevant social groups. These have been identified as inventors, businesses, designers, and laypersons who are involved with 3D printing. While all of these social groups discuss and envision possible futures and potentialities of 3D printing and digital fabrication, their claims of knowledge are often conflicting. This can be seen in their perception of value creation, the way they discuss 3D printing futures, and their perceived ambitions.

Focusing on the actors and groups that interact with a certain technology enables a shift from the discussion of technological artifacts to a discussion of knowledge. In the case of the emerging use of VCRs in the 1970s, the relevant social groups were perceived as the technology makers—the television studios and the users of VCRs themselves. The honing in on the interaction between these social groups reveals how the VCRs not only facilitated predetermined uses, such as time-shifting (the recording of a show and watching it later) but made it easier for users to record and create their own movies. New technological mediators emerged, such as local video rental stores, which significantly impacted the way people could watch movies at home. Instead of going to the cinema, VCR owners could rent and watch movies in their own living rooms. The question then lies in what it means to be a part of a relevant social group. Also, how can we structure and present the opposing views and perspectives of the relevant social groups who interact with 3D printing as a technological artifact?

2.2.7 Relevant Social Groups as Part of a Technological Frame

To structure the interactions among actors in a relevant social group, Bijker (1997) introduces the concept of technological frame [4]. The technological frame is emphasized as a theoretical concept that is established around the interaction with a particular technological artifact. Elements such as goals, key problems, user practice, problem-solving strategies, perceived substitution function, and tacit knowledge are some of the elements that make up the technological frame. These elements might also vary, depending on which social group the technological frame belongs to. As to the question of who are the relevant social groups, Bijker emphasizes the importance of seeing all relevant social groups as being equally relevant, thus making it reasonable to include nontechnologists, such as layperson users, in my sociotechnical analysis of 3D printers.

The technological frame, as illustrated in Fig. 2.3, reveals how the various relevant social groups interact with each other and the technological artifact that is the 3D printer. The 3D printer inventors are concerned with improving and making new fabrication processes to improve the volume of production output, as well as to deliver consistent results. The social group of business managers strives for creating new value systems within a paradigm of economies-of-one, with key problems seen as the necessary operational restructuring of production and delivery. The perspective of the social group of designers is more entangled in exploring material, aesthetical, and process possibilities and in using 3D printing as a developmental design tool. The social groups of laypersons, often referred to as makers, is concerned with conceptualizing and making for private purposes. However, the open sourcing of 3D printing techniques is increasingly blurring the lines between the 3D printer inventors and laypersons. Laypersons are challenged with acquiring adequate proficiencies for material making, as well as having accessibility to 3D printing.

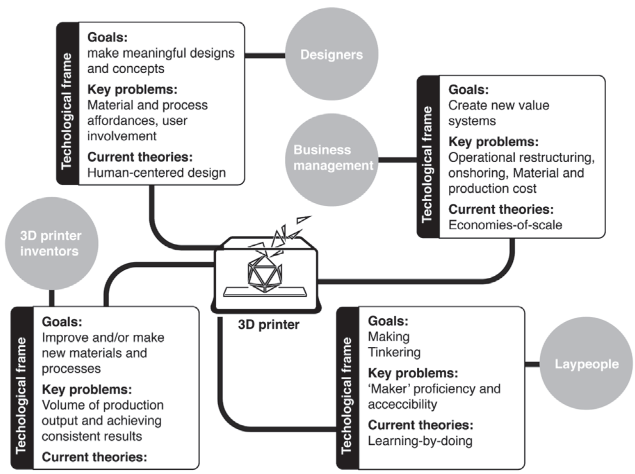


Figure 2.3 The relevant social groups relate to a technological artifact through a technological frame. Illustration: William Kempton.

2.3 The 3D Printer Inventors

The relevant social group of 3D printer inventors apparently forms a critical part of the development of the 3D printer—after all they consist of the researchers and engineers who develop and produce the tools used by those who acquire and use them. So why the need to discuss relevant social groups other than just the machine inventors themselves? The 3D printer makers continuously make new tools and improve the technical workings of the processes. But for whom are they making the machines?

In Chapter 1 Killi briefly discusses the relevant social groups of 3D printer inventors from a legal perspective, such as the German manufacturer EOS, which was banned from the American market due to licensing issues with DTM Systems over the use of printing materials and techniques. Also, as mentioned earlier, the expiry of Crump's patent in 2009 for fused deposition modeling (FDM) printing caused a wave of open-source, desktop-size 3D printers that were increasingly aimed at a consumer market. The developmental story of 3D printers is in fact riddled with legal issues—from the corporate battles of the 1990s and 2000s to the second wave of consumer-oriented desktop 3D printers from 2009 and onward.

2.3.1 The First Wave of 3D Printer Inventors

The initial invention of 3D printing processes, machines capable of automating the process of producing 3D objects by additive means, can be traced back to the 1980s. Spawning out of individual and university research projects, companies such as DTM Systems, Stratasys, and 3D Systems successfully managed to realize the early visions of physically reproducing digital blueprints. At the time, computer workstations capable of processing complex 3D graphics made it possible for engineers and designers to go from physical to digital drawing boards. Computer-aided design (CAD) programs such as Sketchpad had been around for some time and paved much of the way for interacting with digital 2D drawings.

With the development of a second generation of CAD programs, such as CATIA (initially developed by Dassault Systemes for designing fighter jets), drawings could now be viewed and made in all three dimensions, as opposed to drawing-board-like 2D drawings. This development made it considerably easier for designers and engineers to design complex surfaces and geometries, which could then be visualized through computer rendering and simulations. However, the transition from visual to tangible artifacts still relied on laborious handicraft.

In an interview Chuck Hull [40], the initial developer of stereolithography, points to the costly and time-consuming process of developing prototypes and molds for plastic injection as a motivation for creating the first 3D printer. As he explains, the process of designing injection-molded plastic components would be a tedious process in the pre-3D printer era. A tool maker would craft a pattern from a set of technical drawings, which would then be cast into a mold. This process would often have to be redone, as either the original pattern or the molds wouldn't look like or separate as planned. As a result, the development time of even simple plastic objects could take months. Being an engineer himself, Hull envisioned a device that would automate much of the laborious work, which eventually turned into the concept of stereolithography—curing layer upon layer of photopolymeric resin using a scanner-aided laser.

The first generation of 3D printer manufacturers, such as DTM Systems, Stratasys, and Hull's 3D Systems, would continue to grow in the 1990s and serve an ever-expanding industry with specialist equipment for rapid prototyping. As the technology was costly, only large corporate structures could afford such investments, resulting in use mainly by the auto and aero industries. Smaller businesses, on the other hand, would have to resort to acquiring their services from model-making service bureaus. Statistical reports from Wohlers Associates [45] note that by 2004 most manufacturing industries had to some extent embraced RP. In 2003, the total sales of 3D printers amounted to 1864, which gives some indication that the availability of 3D printers was little and far apart. With "low cost" 3D printers such as the Stratasys Dimension SST selling for $25,000, this meant that RP equipment would be prohibitively expensive for smaller organizations, not the least for individual use.

The concept of RP soon came to be closely associated with all things 3D printing. Functional prototypes and aesthetical models accounted for approximately 50% of all applications in the mid-2000s. Although the glory cases were few and far apart, success stories such as the Siemens-developed hearing aids and Invisialign dental braces stand as rapid manufacturing success stories. In fact, Lipson points to the fact that 3D printers as early as the 1980s were sold as the "future of manufacturing" [25]. Killi similarly points out in Chapter 1 that the perceived application areas of these technologies transitioned quite fluidly between being prototyping tools and manufacturing applications.

2.3.2 The Second Wave of 3D Printer Inventors

With the expiry of the desktop-friendly FDM patent by Scott Crump and Stratasys (1992) in 2009 came a second wave of hype around 3D printing [6]. This time, however, the technology was not sold as a prototyping machine for corporate industry. Aside from the RepRap project, one of the first companies to create truly desktop 3D printers on a large scale, MakerBot announced its Thing-O-Matic 3D printer as a "cutting-edge personal manufacturing" tool [27].

Their creators, Bre Pettis, Adam Mayer, and Zach "Hoeken" Smith (Fig. 2.4), having developed the MakerBot concept out of the hackerspace NYC Resistor in Brooklyn, stayed in close association with the Maker community (The name of the company, MakerBot, gives some indication). Made out of laser-cut birchwood and held together with ordinary nuts and bolts, the Thing-O-Matic was itself advertised as an open-source "personal manufacturing" tool and sold as a user-assembled DIY kit for $1099. Boasting a build volume of 96 × 108 × 115 mm^3, the MakerBot printer relied on a plastic filament (either acrylonitrile-butadiene styrene [ABS] or polylactic acid [PLA]) to be heated up, melted, and applied to a build plate through a metal nozzle. 3D models, either self-made or downloaded via their own online repository Thingiverse.com, could be transferred to the printer via a SD card or USB connection.

Figure 2.4 Adam Mayer, Zach "Hoeken" Smith, and Bre Pettis in front of Cupcake CNC prototypes, the first MakerBot product. Image: MakerBot.

Although the company was later sold to Stratasys, which actually held the original FDM patents, MakerBot stood to symbolize the new generation of makers and 3D printer developers. Similar stories can also be told of Ultimaker, its European equivalent. Developed by Erik de Bruijn, Martin Elserman, and Siert Wijnia, who met at a RepRap convention in a maker space called ProtoSpace in Utrecht in 2011, the Ultimaker original shared a lot of the same traits. Constructed as a wooden, laser-cut chassis, the original Ultimaker was sold as a DIY kit for enthusiasts. Having a slightly larger build volume of 200 × 200 × 200 mm^3, the Ultimaker not only had a larger build volume but also a faster print speed due to its Bowden-driven extruder.

The second wave of 3D printer inventors can be seen as increasingly overlapping with the relevant social group of layperson users of 3D printing. Having met at hackerspaces/maker spaces, both the developers of MakerBot and Ultimaker started out by developing and manufacturing their products there, before moving to larger offices. Both companies also emphasize their community-based research structure, by open-sourcing both their hardware and software in online repositories. As a lot of the subcomponents of the fabrication devices consisted of off-the-shelf hardware and electronics (a lot of the desktop printers use Arduino prototyping boards), they were within the price range of curious tinkerers. While the self-assembled MakerBot Thing-O-Matic cost $1099, the Ultimaker was priced at €1194. Countless similar stories can be told of 3D inventor start-ups that have emerged since 2009.

How do the 3D printer inventors shape our understanding of the 3D printer in relation to design?

The first wave of 3D printer inventors positioned the 3D printer as a highly engineering-oriented tool, as it facilitated the manufacture of other things, through prototypes and as visual design representations (VDRs), giving it the name “rapid prototyping.” As mentioned, there also existed early visions of making consumer artifacts directly with the 3D printer. However, it wasn’t until the release of the desktop-oriented 3D printer by the second wave of 3D printer inventors that a similar vision became somewhat realized, although it was targeted toward tinkerers and hobbyist makers.

In the following section, focusing on the business perspective of 3D printing, I will further unpack how 3D printing is interpreted as a tool and means of innovative services and offerings for the pursuit of value creation.

2.4 Business Perspective of 3D Printing

From a business perspective 3D printing is often accompanied by predictions, critiques, and economic forecasts of how it could change future modes of manufacturing, distribution, and work life, ranging from highly positive to negative. Popular news media such as the *Economist* note that the convergence of digital software, new materials, and dexterous, distributed robots will enable a new generation of entrepreneurs to "start with little besides a laptop and a hunger to invent" [28]. Others present more balanced views where AM technologies will continue to improve and supplement, rather than replace current manufacturing paradigms. Sasson and Johnson (2016) envision scenarios where "manufacturers with complex bills-of-material will adopt 3D printing to extract additional scale advantages from traditional manufacturing" [39]. Some critical perspectives emphasize new copyright nightmares [25], while others see AM as fueling a new kind of consumerist frenzy where "hobbyists make legions of *white elephants* out of toxic plastics and [. . .] landfills are chock-a-block with yesterday's badly made fashionable shapes" [2].

2.4.1 Yet Another Industrial Revolution

A recurring claim is often made of how new paradigms of manufacturing will occur, often under the umbrella term of a "3rd industrial revolution" [1, 3]. The industrial revolutions of the eighteenth and nineteenth centuries had drastic social, economic, and political consequences for the lives of those living in developed countries. The improved use of water and steam power, combined with the development of new machine tools, made it possible to materialize new artifacts on an unprecedented scale. Whereas low-volume, decentralized craft production was the previous norm, the industrial rise brought with it centralized clusters of high-volume manufacturers. Starting off with the production of textiles, the notion of economies-of-scale [23] became the mantra for which every aspect of industrial development stood by.

An important aspect of economies-of-scale is the operational optimization of the factory floor. The production of technological artifacts, such as Henry Ford's T-Ford car, required the production and assembly of several thousand parts. Dividing the assembly of the T-Ford along a production line ensured that Ford's cars could be sold within an obtainable price range for millions of people, as long as they chose the color black. This concept of division of labor, with unskilled laborers performing repetitive tasks on the factory floor, strives to minimize the lead time and facilitate high-volume distribution, always aimed at minimizing the sales cost of items. While in modern production environments the methods and processes of material extraction, energy use, and production are being continuously refined, the underlying principle remains the same. Modern companies that can deliver the highest quality for the lowest price have the competitive advantage [32].

The envisioned forthcoming Industrial Revolution, fueled by the potentialities of digital fabrication, is often summarized as a shift from mass production to individual production. The concept of economies-of-scale, where similar plastic artifacts are made affordable due to the gradual down payment of expensive tooling, is complemented by economies-of-one. Here, unique, personal, and individualized artifacts function as the source of competitive advantage. This managerial concept of mass customization [34] focuses on a shift from the offering of generalized mass market products and services to the tailoring of solutions to specific needs, the rationale being that every customer has specific needs that cannot be addressed in a generalized way. Such a shift will necessarily influence many operational aspects of the manufacturing process, from a supply chain that will rely on nonlinear local collaboration to distribution, which will necessitate a direct communication between producer and consumer, and new business models that capture, create, and deliver new values [37]. As to the consequence of emerging and disappearing of professions as a result of increased robotization of labor, Lipson and Kurman (2013) draw similarities with how the Internet made many travel agents obsolete, while at the same time offering new possibilities for travel-related services [25].

2.4.2 Toward Economies-of-One

Because of the potentials for local manufacturing at a reasonable cost (depending on the product) and newfound design possibilities for personalization, AM can be tightly bound with online, customizable services. These were important motivations for making the website fabrikkaho.no (Fig. 2.5), an online sales platform featuring cell phone casings designed and manufactured by design students at the Oslo School of Architecture and Design (AHO). The concept, titled Fabrikk AHO (translates as Factory AHO in English), presents 21 individual design projects that are designed specifically for AM. The design in Fig. 2.5 shows a smartphone casing featuring an integrated kickstand and cardholder that allows for user customization of both texture and a 10-character phrase. While serving as a visual example of how online customization can be facilitated, the idea of economies-of-one can be entwined in product service offerings to various extents.

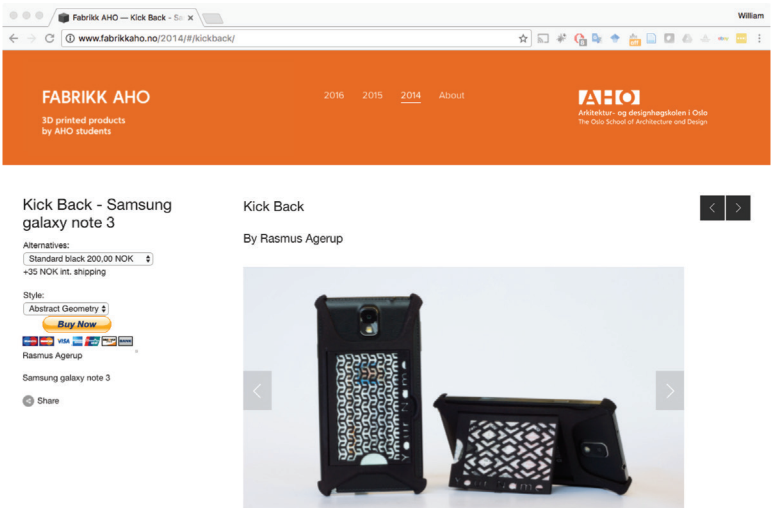


Figure 2.5 A 3D-printed kickstand for the Samsung Galaxy Note 3 cell phone, with customizable patterns, sold as a limited-edition product by design students at www.fabrikkaho.no. Design: Rasmus Agerup.

Later in this book Monika Hestad analyzes the role of AM in developing the eyewear brand Mykita, through a product and branding framework. As a part of her analysis she discusses both the internal and external drivers for Mykita as a brand. Mykita, which was founded in 2004, can be seen as a relative newcomer to the eyewear industry, mainly dominated by major fashion houses. Mykita presents itself as a modern eyewear company that combines modern production technology with traditional craftsmanship.

Under the banner of "Handmade in Berlin" its Mylon series brands itself as being both technologically innovative and sporty, honest, and imperfect. Produced in-house with powder-based SLS 3D printers, the Mylon series, which was initially developed in 2007, doesn't offer any individual user adaptation but, instead, offers a wide spectrum of variations, currently consisting of 51 different styles.

The company's website (mykita.com) presents Mylon not only as a product series but also as a complex material composite that is prepared in a series of stages. Starting off with the fine-powdered polyamide powder commonly used in SLS printing, the laser-sintered artifact is then cleaned, sanded down, color-dyed, and left to cure. It is conceivable to think that Mykita would have had the initial idea of making user-customizable glasses when the initial 3D-printed glasses, Mylon, were conceptualized. For Mykita, this would bring large implications for both its supply chain, as no two glasses are the same, as well as the customer journey. Where should the customer have his or her face scanned? How could the glasses be adjusted not only ergonomically but also as per the customers' individual preferences?

Almost 10 years after the development of Mylon, Mykita announced in 2016 its entry into the area of customizable eyewear through its MyVeryOwn series, which extends its material composite to incorporate individual ergonomic considerations. Still, the user journey for Mykita's personalized glasses starts with the physical shop, as shown in Fig. 2.6. The recent proliferation of 3D printing creates an innovative surge in technologies that supplement it. Consequently, new businesses and entrepreneurs fill in the need for specialist services and technologies, such as 3D facial scanners and optimization algorithms, that only recently have made MyVeryOwn possible. In Chapter 4, Hestad gives further insight into the branding of AM through the Mylon case.

How does a business perspective shape our understanding of the 3D printer in relation to design?

While the inventors of 3D printers removed some of the traditional barriers related to the fabrication of goods, their role as a manufacturing tool requires specific strategies for integration. The social group of business managers applies managerial concepts, such as economies-of-one, in order to leverage the potentialities of 3D printing into its value creation process.

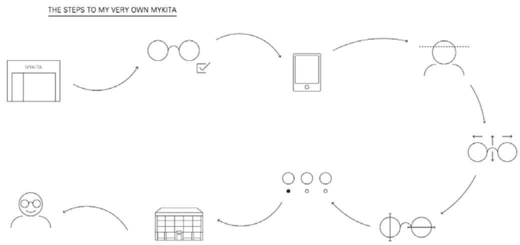


Figure 2.6 The figure shows how Mykita envisions its new services, focusing on personalization of its MyVeryOwn subbrand. Much like its currently available products, the first step on the user journey is found in the shop. Image: Mykita.

In the following section, these potentialities are further unpacked, through the perspective of design practice.

2.5 Designers' Perspectives of 3D Printing Futures

From the perspective of design, 3D printing has traditionally been used as a developmental tool for making VDRs, such as prototypes or mechanical verifications of to-be artifacts. Early adopters of RP, such as General Motors and Electrolux, rationalized the use of RP as a way to decrease time-to-market for new products. Early 3D printing technologies became important features in their corporate development strategies. Not only did this apply to the initial "fuzzy front end" [21] stages of a product development process, it also served a purpose for the marketing of new products, through beta testing, and in making visionary concepts.

Figure 2.7 shows the conceptualization of a computer mouse whose main components include a tactile, wooden surface mounted on a principle SLS-printed structure. Tasked with the challenge of conceptualizing a digitally fabricated computer mouse, the designer chose wood as the tactile material toward the user's palm. As opposed to carving the wood by hand, or using a computer numerical control (CNC) mill to subtract the form from a solid piece of wood, the designer created several rapid iterations of a 3D-printed mold using a desktop 3D printer. The mold was then placed in a vacuum-forming machine and used to bond several layers of wooden veneer together with a plastic polyethylene terephthalate (PET) (commonly found in soda bottles) sheet acting as the female part of the mold. Although the mold was rendered unusable after the initial trial, due to the low melting temperature of the PLA plastic used by the desktop printer, it was sufficient for the conceptualization of a novel manufacturing technique of a 3D-printed computer mouse. This example shows the dynamic use of fabrication tools, both traditional and digital, by designers who conceptualize new products and services with 3D printers.

Figure 2.7 A digitally fabricated computer mouse using several production techniques. Design: Hans-Martin Erlandsen; photo: William Kempton.

The student's work corresponds to a categorization of the use of 3D printing from the perspective of product design, which can be placed in three separate categories of actual developmental product design work [20]. The primary, and traditional, use of 3D printers lies in their ability to create design representations, such as visual models or quantitative structures of a physical design. Secondly, the use can be defined through its role in a manufacturing process, such as the making of the mold used for veneering of the computer mouse in Fig. 2.7. Thirdly, the use of a 3D printer in a developmental process can be defined as manufactured objects, where it acts as a production platform of end-use artifacts. This last categorization is often described as AM in the literature as well as in popular media.

2.5.1 Design and Additive Manufacturing

The shift in focus, from seeing 3D printers as developmental prototyping tools from an RP perspective to considering them as a means of production from an AM perspective, is a transformative shift. While designers and engineers were early adopters of 3D printing for making prototypes, new users of 3D printing are pushing forward an integrated development for conceptualizing, designing, and producing innovative new products. The beneficial abilities of AM production have been the basis for tentatively grouping [19] the potentials of AM as enhanced design, custom design, and computational design.

Both *custom* and *enhanced* can be seen as ways of describing a design or making use of it in the development of a product. Shortly described, a custom design may refer to a design where the dimension and style are based on unique, individual preferences. Enhanced design may refer to the improved capabilities of the AM process, such as making complexity feasible, while computational design relates to a process of algorithmic computation. Envisioned as artifacts, these potentialities can be seen as coexisting, as in the example of the animalistic coffee cups seen in Fig. 2.8. Here, the aesthetics of the design concept is envisioned around a series of dog-like gestures.

Figure 2.8 3D-printed, customizable coffee cups in ceramic, based on the movements of an animal. Design: Izelin Tuulikki O. Tujunen; photo: Inger Steinnes.

2.5.2 Designing with Technology

As a developmental process, human-centered design (HCD) is pulled toward the creation of products and services that are feasible and create value for their users. At the same time, increasing demand for digitalization, connectivity, and systematization create a need for designers to adapt to new emerging technologies. This is seen in areas of both product design as well as HCI, where new technological platforms such as virtual reality (VR) environments, 3D printers, and mobile platforms invite for new novel uses and implementations into current contexts. More often than not, designers are challenged with satisfying the relationship between tackling the creation of meaning and technological innovation.

As canons of the discourses on HCD and innovation, Norman and Verganti (2012) analyze the relationship between technology and meaning in their discussions on radical innovation versus HCD [30]. They argue that the incremental nature of HCD is adapted to developing meaningful designs, while radical innovation pushes for technological innovation. Their theoretical frame sets technology and meaning as two dimensions of innovation, with the biggest changes in innovation coming about when both dimensions change. Such technology epiphanies come about when new contexts are facilitated through technological innovation.

Pioneering in design research in AM over the last two decades, Steinar Killi (2013) discusses the need for the product design discipline in looking beyond an isolated technological push, a view often adopted by the corporate AM industry, which is the traditional innovator of digital fabrication technology [19]. His recently developed approach (see Chapter 3) to product design and AM, labeled "AICE" (adapt, integrate, compensate, and elongate), outlines a way of designing meaning through technology as opposed to designing from technology. I argue that such a view is relevant both in the case of HCD development as well as for gaining a situated understanding of the emerging role of 3D printing technology. Such a view forces us to consider the deeper, underlying discussion of technology in relation to design.

2.5.3 An Undetermined View of Design

In discussing philosophical approaches to technology, Ihde uses the notion of designer fallacy to explain the notion of designing intents with technology. Ihde calls for an unpacking of the complex relations that over time are played out between designers, technological entities, and the end-users of technologies. The notions of intentional fallacy in literary theory argues that a text can be established only after the author's intentions are uncovered. Similarly, Ihde develops an argument based on the concept of designers employing purpose and use in technology, which is critiqued by Ihde. This notion that intent is not possible to determine fits into Ihde's undeterministic ontological view of technology and society. Such an undeterministic view is useful for our discussion of design, as it allows us to consider the technological materialities, qualities, and possibilities of 3D printing in a way that is useful to our view of design as a situated, open-ended process.

Such an open-ended view of 3D printing is similarly taken up by Peter Troxler [41] in his discussion of community-based Fab Labs as users and developers of 3D printing technology. Troxler also discusses the emerging awareness of value creation, but from the point of view of community engagement. His discussion of technology takes on an attitude of "you don't own it if you can't open it," arguing that technological empowerment is necessity for critical use of technology.

From an HCI point of view of technology and digital fabrication, Matt Ratto takes a similar stance in his use of freely available software for materializing digital information [35, 36] in his 3D printability project, which seeks out to make below-the-knee prosthetics.

How does a design perspective shape our understanding of the 3D printer in relation to design?

In developmental design practices, the use of 3D printing tools can be placed within three categories: as design representations, as a toolmaker for molds and fixtures in a manufacturing process, and as manufactured end-use objects. The latter category, which can be described as AM, comes with its own set of potentialities, which are tentatively customizable, enhanced, and computational.

However, in a wider scope of design practice, which is found outside of the confines of consumer-oriented practices, 3D printing can be seen as a tool that enables and empowers design engagement in new contexts and uses. The following section, which focuses on the social group of layperson makers, can be seen as one of the new contexts.

2.6 A Layperson's Perspective of 3D Printing Futures

As opposed to expert practitioners who are proficient in their given profession, a layperson can be described as a person without any specialist knowledge. With desktop fabrication becoming increasingly available in schools, in libraries, at home, and in community spaces, such as FabLabs [43], it opens up opportunities for layperson participation in both formal and informal material making. In the section on the 3D printer inventors, I discussed how the recent developments in desktop 3D printing have strong ties with maker spaces. These informal meeting grounds are places where companies such as Ultimaker and MakerBot were founded and where initial production of their tools was taking place. In addition, these arenas serve as a playground for an increasing number of enthusiasts who make and share ideas with each other. Laypersons' involvement in 3D printing, therefore, forms a relevant social group in my analysis.

2.6.1 A Layperson as a Maker

Layperson involvement in 3D printing is often closely linked with the umbrella term "the Maker Movement." Popular magazines, such as *Make* magazine, review and discuss the evolving market of desktop 3D printers, in addition to organizing popular festival concepts such as Makerfaires. Independent hackerspaces also help mediate the use of digital fabrication tools as personal, desktop-friendly tools. On reflecting on the emergence of the Maker Movement, Dale Dougherty (2012), the founder of *Make* magazine and Makerfaire, emphasizes a return to a material engagement that makes people more than just consumers. Dougherty describes a "maker" as a holistic ideal—"We all are makers: as cooks preparing food for our families, as gardeners, as knitters" [9].

Since the release of certain 3D printing patents [6] the availability of desktop 3D printers has gradually increased among nonexperts. From the initial self-replicating open-source RepRap tools to preassembled tools such as Ultimaker, 3D printing tools and commodities are becoming increasingly accessible for layperson use. 3Dhubs.com, a social distribution platform for 3D printing services, notes that user-to-user 3D printing services are now available in every continent, with cities such as Milano and Amsterdam hosting up to 300 individual hubs each. While local users are supplying laypersons in many of these European cities with prototypes and models, access to local expertise is also happening through initiatives such as maker festivals and in local maker spaces.

2.6.2 Making in a Learning Environment

The image in Fig. 2.9 shows a group of high-school students assembling an Ultimaker 3D printer at a local maker festival in Oslo. The kit was donated by local organizations and is distributed to several high schools in Oslo. As the printer contains a lot of moving parts, it is prone to jam. By assembling the kit themselves, the students get an insight into the inner workings of the technology, thereby making it easier for them to identify future problems.

Figure 2.9 Local high-school students are assembling Ultimaker 3D printers at a local maker festival in Oslo. Photo: William Kempton.

An increasing number of educational environments are adopting digital fabrication tools in their curriculum, as it is coming to represent the twenty-first-century equivalent of a shop class. Organizations such as MakerEd, which are developing resources and online libraries through the vision of "Every child a Maker" [26], are some of the many organization that see 3D printing as a powerful educational tool. Although the use of digital fabrication can be seen as relevant for its engagement in both math and engineering, it is important to consider that engagement in 3D printing doesn't necessarily need to relate to any specific competencies. As we are arguably in the "early phase of a wide-scale revolution in tangible creation" [10], the adoption of digital fabrication in the day-to-day culture of children and youth can have positive educative traits.

Performing tasks, failing, and redoing them as a reflective process reflects a mode of learning that emphasizes experience.

As an influential educational reformer, John Dewey [8] argued that there are different forms of experiences, agreeable and disagreeable, that naturally affect future experiences [8]. Dewey criticized the contemporary education of his time in that it built on various established routines for teaching existing knowledge, which would later be imposed on the younger generations. Instead, he proposed a mode of experiential learning that is linked to real-world objects and not bound by the model of current natural science (STEM) education way of organizing subject matter [8]. This ideal of an experiential learning process was later formalized by Kolb [22], who supplemented the idea of figurative representation of experiences with a transformation of that representation [22]. In such a way, the theory of experiential learning relies as much on making as it does on reflecting.

Digital fabrication tools have the ability to facilitate an experiential learning cycle. The 3D printer is in fact a tool for making physical, real-world artifacts. And as with most making processes, its very nature is incremental. An idea is deceived, deliberated upon, and conceptualized. However, the concept of 3D printing requires extensive knowledge in a variety of fields (although the inventors of desktop printers would claim otherwise). Not only does the 3D printer rely on a series of subtools, such as apps for preparing content to be fabricated, it also relies on a material input. As the 3D printer is a tool for fabricating real-world artifacts it requires physical ingredients, usually in the form of plastic, and also a digital blueprint.

How does a layperson perspective shape our understanding of the 3D printer in relation to design?

Layperson engagement in 3D printing is an increasingly relevant topic for design. It relates to discussions on consumerism, education, and distribution and production of goods and artifacts. It can also be seen as a tool for opening up the notion of making as a form of literacy and the ability to question the consumerist patterns that we live by. These are some of the central ideals of the Maker Movement.

2.7 Discussions and Conclusions

2.7.1 Summarizing the Perspectives

In summarizing the various perspectives presented in this study, digital fabrication tools can be seen by the first generation of 3D printer inventors as engineering-oriented tools, facilitating the manufacture of other things, through prototypes and as VDRs. While RP remained the dominant purpose, there also existed early visions of making consumer artifacts directly with the 3D printer. However, development of the desktop-oriented 3D printer by the second wave of 3D printer inventors somewhat realized this concept, targeted toward tinkerers and hobbyist makers.

The social group of business managers strives to create new value systems within a paradigm of economies-of-one, with key problems seen as the necessary operational restructuring of production and delivery.

The perspective of the social group of designers is more entangled in using 3D printing as a developmental design tool. The developmental use of 3D printing can be placed within three categories: as design representations, for making tools such as molds and fixtures in a manufacturing process, and as manufactured end-use objects, often referred to as AM. In the periphery of consumer-oriented design practices, 3D printing is increasingly explored due to its novel material, aesthetical, and empowering potentials.

The technological frame of laypersons, often referred to as layperson makers, is concerned with conceptualizing and making for private consumption. However, the open sourcing of 3D printing techniques is increasingly blurring the lines between the 3D printer inventors and laypersons. Laypersons are challenged with acquiring adequate proficiencies for material making, as well as having accessibility to 3D printing tools.

2.7.2 3D Printing Futures

The story of the development of the 3D printer is by no accounts written. In an interpretive analysis such as this, there can be several analyses that forward an argument of sociotechnical development.

In any such analysis, the matter of choosing which relevant social groups to discuss is equally important. For this chapter I have selected a set of social groups that allow me to analyze 3D printing not only as an instrumental tool for experts but also as an increasingly democratized tool for making. Through my analysis of recent social and technical events I attempt to build an understanding for evaluating contemporary as well as future understanding of digital fabrication. And as much as my analysis of the development of 3D printing up to now is portrayed in the light of my selection of relevant social groups, the future visions of 3D printing are increasingly up for interpretation.

As there is a continuing amount of interest in the future role of digital fabrication, so is the continuing amount of interested parties. The second wave of 3D printer inventors, such as Ultimaker and MakerBot, developed and made their first fabrication tools out of maker spaces, primarily serving a clientele of self-proclaimed makers. While newly founded companies such as these continue to grow, the next wave of 3D printer inventors are of a different sort. Large technology companies not previously engaged in 3D printing, such as HP, recently stated in a press release that their future growth now lies in digital fabrication. This was later supported with the release of a newly developed fabrication technology, HP Multi Jet Fusion, which builds on much of their knowledge and expertise from traditional inkjet printing. While HP develops the fabrication process, it closely collaborates with the chemical industry for developing new materials. Companies such as BASF (Badische Anilin und Soda Fabrik), a major chemical and plastics manufacturer, might have a considerable impact on the employment of AM in future contexts. As they improve and create new materials for AM, they make themselves relevant as far as a social group goes.

2.7.3 Constructing a View of Sociotechnical Development

Through an argument that is based on a social constructivist idea of technological development as being socially constructed, this book chapter analyzes the emerging social practice, mediation, and knowledge being brought through the development of the 3D printer.

These theoretical frameworks that have been applied are brought in from critical theories of STS, such as those by Feenberg, Ihde, and Bijker, which argue for a view on technological development as being undetermined.

The theoretical concept of relevant social groups and technological frame is introduced through the story of the development of home video entertainment. Similarly, the development of the 3D printer can be seen in the light of its relevant social actors. For my analysis I have focused on the relevant social groups as seen from a design-relevant perspective. The 3D printer being a tool that facilitates the making of things, I argue that it has great implications for the way design is being conducted, as well as its emerging role as a tool for democratizing design for the current and future uses of the digital fabrication tool.

Appendix: Technologies for 3D Printing

The 3D printer is a technological device for additively fabricating curated, sensory content. Like other fabrication devices, such as sewing machines and inkjet printers, the 3D printer delivers its medium in the form of physical artifacts that can be touched and felt. Whereas an inkjet printer prints text and images on a 2D surface, the 3D printer fabricates 3D artifacts according to a set of predefined instructions. As a technological principle, 2D printing can be divided into many different subprinciples along a historical time line—from woodblock printing, which dates back to early Asian culture, to the Gutenberg press, which initiated the European age of printing. More recent innovations include the introduction of photocopying by Xerox in the early 1960s to inkjet and laser printers, which gave way to the concept of desktop publishing.

Similarly, 3D printing techniques make up a wide-ranging set of tools, as the formats, or processes, have distinct properties (Fig. A.1). Some processes are unique in the way they reproduce large, transparent artifacts, while others create small, highly detailed objects. One could also speculate that the reason for the coexistence of all the different 3D printing processes is that these devices have only recently become domesticated. Only after certain patents for digital fabrication processes expired, namely the patent for filament deposition modeling (FDM) printing (Fig. A.2c) developed by Scott Crump [2], did the desktop 3D printer become available as a domestic appliance. Starting with the open-source development of the self-replicating RepRap printer [1], the market for relatively low-cost FDM printers has proliferated. Companies such as Ultimaker, WASP, Printrbot, and Zortrax, to name a few, sold printers by the thousands to enthusiasts all over the world.

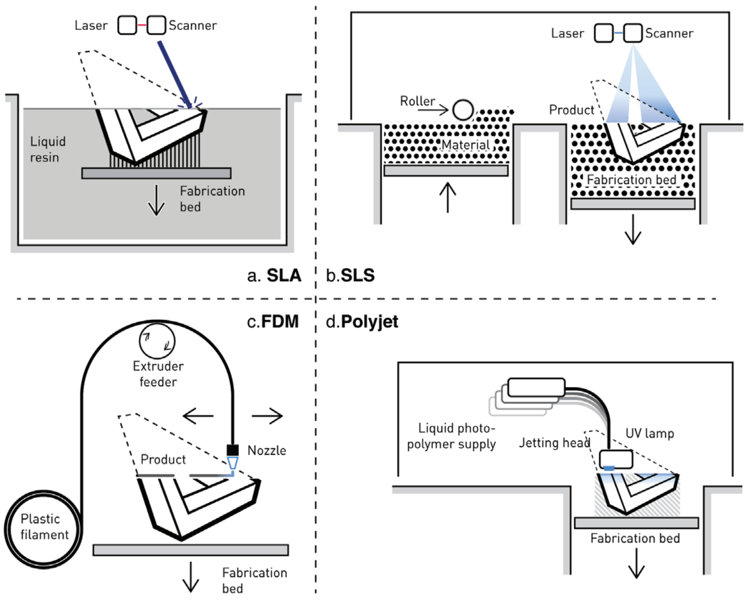


Figure A.1 Some of the processes that make up 3D printing: (a) Stereolithography (SLA) involves the use of a photopolymeric liquid, which is selectively hardened by exposure to light. (b) Selective laser sintering (SLS) deposits thin layers of power-based plastic, such as nylon, which is heated up and sintered together by a powerful laser. (c) Filament deposition modeling (FDM) feeds strings of plastic filament through a nozzle, which gradually builds up the artifact. (d) PolyJet, similar to the concept of SLA (which uses a photopolymeric liquid as a principle building material) deposits and selectively hardens voxels, 3D pixels of material, in thin layers. Illustrations: William Kempton.

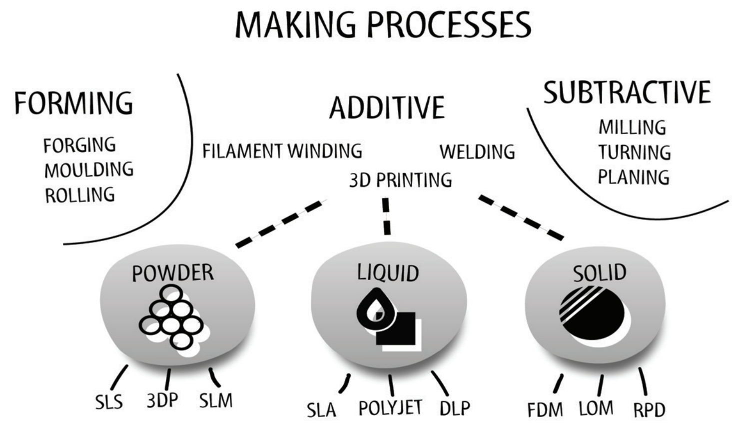


Figure A.2 The processes for making can be described as being either forming, additive, or subtractive. 3D printing is an additive process as it is operates by binding or bonding material together in a layerwise fashion. Illustrations: William Kempton.

A.1 The Principle of 3D Printing

Much the same way as you would bake a cake, the principles of 3D printing usually involve a recipe, a set of ingredients, and a mechanism for bonding, curing, or sticking them together. But unlike the manual fashion in which you would compose the cake, the 3D printer eliminates the need for intervention by automating the forming process. The different technologies that make up 3D printing require both different recipes and ingredients, as the processes differ. Some processes, such as FDM, apply strings of plastic polymer in a layerwise fashion, while others, like SLA, rely on a liquid that reacts to light. There are powder-based machines that spread layer upon layer of fine-grained plastic, gypsum, or metal powders onto a surface, which are then bonded together. Sheets of paper may also be cut, glued, and stacked together to form a 3D object.

Current powder-based processes create precise and structurally strong objects with a high degree of design freedom. Liquid-based processes imitate well-known materials and materialities (such as transparency, translucency, and flexibility). Lastly, solid-based processes such as desktop 3D printers are low-cost technologies often used for prototyping. Figure A.3 illustrates how the many making processes of 3D printing can be described as being powder based, liquid based, and solid based. What they all have in common is that they are *additive* forming technologies.

Figure A.3 A series of cylindrical shapes that are made using various digital fabrication techniques. Models: Christopher Pearsell-Ross; photo: William Kempton.

The recipe for which the 3D printer gets its instructions is a crucial part of the digital fabrication process. Much the same way a craftsperson, chef, or laborer relies on a set of instructions to make a product, the 3D printer relies on a set of inputs to perform. The 3D printer is in fact a "CAD-based automated additive technology" [3] as it relies on a digital blueprint typically from a computer-assisted drawing (CAD) program. These drawing tools were once restricted to "experts" as they were expensive and required a steep learning curve. However, as the popularity of 3D printing has increased, so has the availability of CAD programs to nonexpert users. New products and services that focus on nonexperts are being promoted from companies such as Autodesk, Solidworks, and Onshape. This new generation of CAD programs is becoming more accessible through new pricing schemes, online tutorials, and the fact that they are cloud based. This again opens up for use on mobile devices, such as smartphones and tablets.

A.2 Additive Manufacturing as a Making Process

Natural phenomena that create rock formations or allow trees to grow are natural making processes that construct and continuously evolve the earth's surface. Similarly, the act of making objects and artifacts through tools and processes is an important aspect of human endeavor. But as opposed to natural processes, such as photosynthesis, ocean currents, and seismic activities, tools made by people are constructed, made artifacts. As they are put to use, as part of a process, the artifacts become part of a technological system. In essence, the objects and artifacts that we surround ourselves with every day are all products of technological making processes. And as with nature, these methods of making can roughly be described as *subtractive*, *forming*, or *additive* processes (Fig. A.2). As erosion chips away at soil and rock, it forms new land and scenarios. Similarly, man-made *subtractive* technologies rely on solid pieces of material such as wood, stone, or foam to be cut, milled, planed, or trimmed away. And whereas these technologies once relied on manual labor, such as a craftsman's chisel, digital fabrication tools such as computer numerical control (CNC) milling have become its modern extension.

As shells are bones are left in the ground for millions of years, the surrounding sand and soil leave fossilized imprints of what was once a living organism. As the organic material is replaced by minerals inside the cavity of the shape, nature manufactures an internal mold of itself. Similarly, man-made processes for molding, forging, rolling, or deforming material into new form can be characterized as a *forming* process. In the manufacture of plastic parts, a tool, containing the hollow cavity, is used to reproduce exact, positive replications of itself.

As for *additive* processes, these are also abundant in nature, for example, trees and plants that grow and wounds that heal. However, in the manufacture of objects and artifacts, the process is relatively novel. As an additive process, 3D printing is capable of transforming material into new purpose, without the need for a predefined tool or mold determining the shape of the artifact being made. A coffee cup that has been slip-casted in a mold may be identically reproduced thousands of times from the same mold. A coffee cup made by additive means, however, may be reproduced thousands of times, each with a unique shape. There are many potentialities of additive processes that go beyond aesthetic freedom, such as material composition and potentially less material consumption. Some even claim 3D printing has the potential to greatly democratize the acts of both designing and manufacturing things [46].

In the following sections we further explain the various additive manufacturing technologies. These can be seen as powder based, liquid based, and solid based.

A.3 Powder-Based Additive Processes

A.3.1 Selective Laser Sintering

A.3.1.1 SLS background and process

SLS (Fig. A.4) has as one of the principal methods of rapid prototyping a history of producing prototypes and tools for other manufacturing methods, such as injection molding. The technology, first commercialized by Carl Deckard in the 1980s, is currently one of the most commonly utilized technologies for making both prototypes and end-use parts (additive manufacturing).

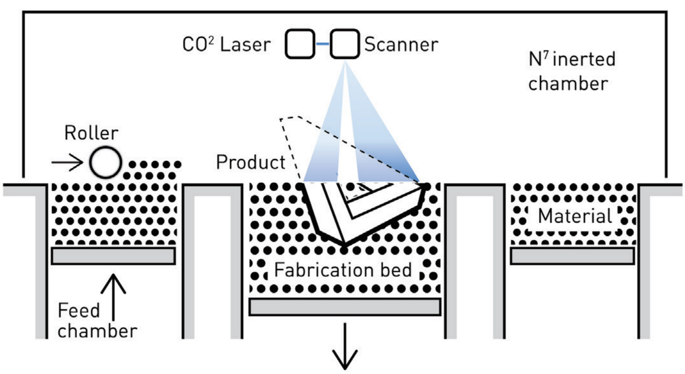


Figure A.4 SLS process principle. A powerful laser sinters particles of material together, layer by layer.

In preparation of the fabrication process, a large amount of the material is filled into two separate feed chambers, one on each side of the fabrication bed. The SLS build chamber is then filled with nitrogen-rich air and heated to approximately 170°C (depending on the material), while a base of material, usually polyamide, is spread out by the feeder mechanism (while 3D Systems employs a roller, EOS uses a wiper due to patent disputes), bringing material from the feed chambers at each bypass. The fabrication bed is held just below the material melting temperature, before a 12°C increase caused by the passing laser sinters the material granulates together. New layers of material are fed over each other and repeatedly bonded. The build process, depending on the load, fabricates approximately 15 mm of material an hour.

After the fabrication process the entire fabrication build is set to cool down to below 70°C, before the fabrication "cake" is lifted out to a cleaning station. The excess nonsintered material is often partially reused. The fabricated artifact is then blasted with abrasive glass powder to clean out the remaining powder.

A.3.1.2 Design considerations for SLS printing

The ability to fabricate strong isotropic parts, in addition to the nonsintered powder acting as a support for cantilevered parts, makes it possible to create a wide variety of complex shapes. It is well suited to fabricate open-lattice structures and perforated surfaces as both large solid geometries as well as flat planes may suffer deformation. As the material is self-supported, free-hanging shapes can be printed inside a cavity. However, if the cavity is closed, material will be trapped in the cavity. An important design consideration is to create holes for nonsintered material to exit. Common to all the powder-based processes is that the surface finish will be matte and porous and slightly water permeable. Postprocessing of the fabricated artifact is common, from spray painting to dyeing or polishing.

A.3.1.3 Materials in SLS processes

A common material used in the SLS process is white PA-12 polyamide (PA) powder, which gives strong yet flexible parts with a high material finish. Other materials, such as glass-filled or carbon-filled PA, provide unique material capabilities such as increased material stiffness and thermal conductivity, to mention a few. It is also possible to fabricate using flexible, elastomeric materials, as well as HD-PE, PET, polystyrene, PA-11, and PA-6.

A.3.2 Inkjet Powder 3D Printing

A.3.2.1 3D printing background and process

3D printing (Fig. A.5) is a relative newcomer to the market of 3D printers, developed by researchers at MIT in the early 1990s and made available in 1993. The ZPrinters, as they were initially called, operate in a layerwise fashion, selectively fusing cross sections of material much like any other 3D printing processes. Instead of using heat to fuse the cross sections, which are filled with gypsum powder, an inkjet printer head moves around depositing droplets of binder liquid, thereby fusing the gypsum. The process makes it possible to fabricate mockups and models in greater speed compared to other technologies, at lower cost, and with the ability to fabricate colored artifacts.

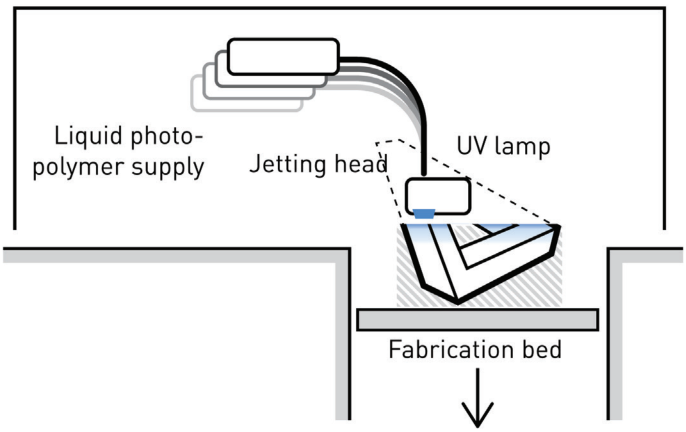


Figure A.5 3D printing deposits a liquid adhesive onto a layer of gypsum powder through an inkjet print head.

The use of plaster-based materials, in combination with a binder material that reacts with the plaster, is unique to 3D printing technology. While successively depositing layer upon layer of fine-grained plaster powder, a set of color print heads moves and selectively deposits the binder, similar to an inkjet printer. Whereas an inkjet printer prints on paper, the print heads in the 3D printing machine print directly onto the gypsum surface before a roller spreads another layer of powder from a feeder. The amount of binder that is deposited onto the surface varies: On a dense shape, the outer shell is fully saturated with both color and transparent binder, while the core of the shape is partially filled with binder. Artifacts are fabricated with relatively low temperatures. Although there is no heat fusion, the binder liquid causes the plaster to harden and radiate heat. After processing, artifacts are usually left in the machine's build chamber to dry and cool down. Once taken out of the fabrication chamber, the artifact is carefully brushed clean of material residue.

A.3.2.2 Design considerations of 3D printing

3D printing technology is often used for making prototypes and models. The plaster material used in the process is fragile, brittle, and slightly porous. The material is therefore well suited to grinding and polishing. The relative fragility of the material makes it unfit for functional or mechanical prototypes. When constructing for 3D printing, a wall thickness of less than 2 mm and details of less than 1 mm should be avoided. As the part is fragile during unloading, any unsupported walls or cantilevered parts should be at least 3 mm thick. Part orientation in the fabrication bed may affect tolerances and should be considered in the process.

A.3.2.3 Materials in the 3D printing process

While there are few officially compatible materials that work with 3D printers, third-party suppliers have developed ceramic powders with accompanying binders, which make parts that can be burned in a kiln. Although the plaster is fragile when taken out of the fabrication chamber, resins or mineral salts may be infused onto the surface for increased strength, saturation of color, or smoothness of surface.

A.3.3 Selective Laser Melting

A.3.3.1 SLM background and process

The SLM process (Fig. A.6) was initially developed by the German Fraunhofer Institute and became commercially available in the early 2000s. SLM is characterized by its ability to make high-value, low-volume, end-use parts from an increasing inventory of metals and alloys. The fabrication process has been adopted for additive manufacturing purposes by specialized industries, such as medical orthopedics and aerospace industries.

A fine-grained metal powder is spread across the fabrication bed, while cross sections of the 3D model are selectively fused together in a layerwise fashion. As opposed to other processes for metal fabrication, such as direct metal laser sintering (DMLS), SLM fully melts the powdered metal into a homogeneous mass using a powerful laser with several hundred watts. As the process is time intensive and therefore costly, it is considered a manufacturing process of end-user parts or for tooling, as opposed to making design representations.

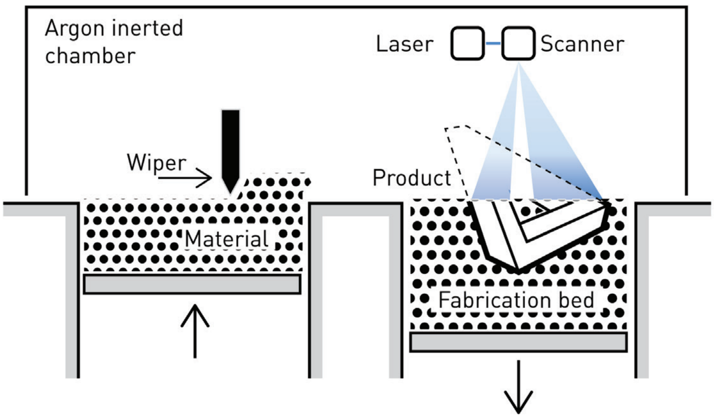


Figure A.6 Fine particles of titanium, steel, and other metals are spread over a thin surface before being exposed to a high-power laser, which welds the particles together.

A.3.3.2 Design considerations of SLM printing

As opposed to plastic powder-based processes, fabrication with metal powders may rely on additional support structures if the surface is less than 45°. Also, surface finish is best if the surface is fabricated in an upright position [9]. Support structures may require additional postprocessing.

Parts made in SLM may be of varying accuracy, as overhangs and holes may be subject to material curl, a condition where the top layer of melted metal powder lifts up from the fabrication bed. When designing for SLM, details of less than 0.3 mm and a wall thickness of less than 0.5 mm should be avoided.

A.3.3.3 Material in the SLM process

Apart from being powdered, the materials that can be processed with the SLM process need certain flow characteristics. Commonly used materials include stainless steel, titanium, aluminium, cobalt chrome, and tool steel.

A.4 Liquid-Based Additive Processes

A.4.1 Stereolithography

A.4.1.1 SLA background and process

Stereolithography (SLA) was first patented by Chuck Hull in 1986 and made into a working machine in 1987 and is arguably the founding principle for 3D printing. As with SLS, the technology was initially developed for rapid prototyping, making highly detailed visual models for the development process of products. Fabricated parts were brittle and vulnerable to light exposure, limiting their functional use. However, due to recent developments in material and process, SLA has become an important tool in the shift toward additive manufacturing.

The liquid photopolymer used in the fabrication process is sensitive to light and can be highly toxic, requiring special care when preparing the process. Upon contact with a UV laser, a thin layer of liquid is solidified to the fabrication bed (Fig. A.7). Although there are several principles for the fabrication process, they all have in common that the UV laser cures a complete layer before the fabrication bed moves in preparation for the next layer to be fabricated. The object either emerges from the vat of liquid or is gradually submerged into it. Between the curing of each layer, surface tension between the liquid and the solidified polymer is broken by either tilting the vat or sweeping over the most recently fabricated layer with a paddle. Either way, the object that is being made requires a set of support structures that make the parts stick to the fabrication bed, as well as allowing for overhangs to be constructed.

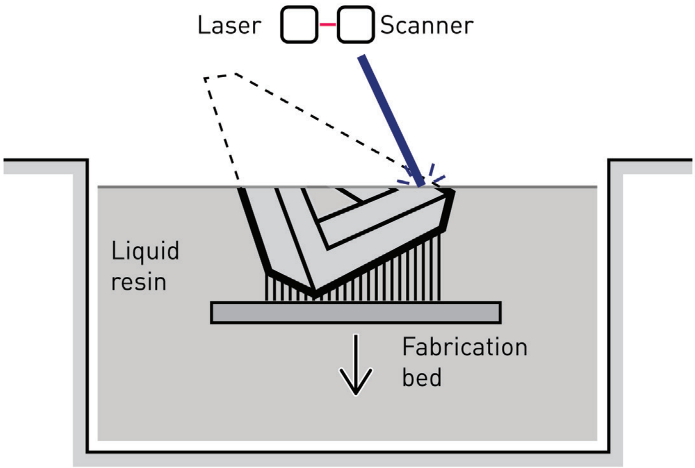


Figure A.7 A photopolymeric liquid is exposed to the light of a laser, which solidifies the liquid.

When the process is completed, the fabrication bed is removed, with the fabricated object stuck onto it, before it is broken loose and cleaned with alcohol-based chemicals. Depending on the material choice, the part is either posttreated with other chemicals or further cured under intensive UV light for a short period.

A.4.1.2 Design considerations of SLA printing

With layer thicknesses varying from 0.025 mm to 0.2 mm, the SLA printer is considered a process capable of producing high-resolution parts, capable of producing surfaces of near-injection-molded quality. The process requires additional support structures, which may require postprocessing. To minimize the amount of support structures needed, parts may be either tilted to minimize overhangs or specifically designed with angled overhangs. A common rule-of-thumb is to avoid overhangs of less than 30°.

A.4.1.3 Materials in the SLA process

The liquid-based materials used in the SLA processes are complex chemical compounds tailored specifically for each SLA printer. While both solid- and powder-based materials are based on common thermoplastic polymers such as PA, PLA, or ABS, the base materials used in SLA are often described in relation to their characteristics.

Materials are often described as ABS-like, flexible, castable, tough, or extreme. Clear materials, which are a unique characteristic of liquid-based processes, may be used to create translucent or near-transparent parts with varying thicknesses. While SLA materials have traditionally been seen as fragile, toxic, or vulnerable to light exposure, recent material developments are gradually rendering these limitations obsolete.

A.4.2 PolyJet

A.4.2.1 PolyJet background and process

In 2000, Objet Geometries, now a subsidiary of the 3D printing giant Stratasys, launched its first PolyJet 3D printer. Since then PolyJet and other multijetting technologies are available from several companies, such as 3D Systems. By selectively depositing droplets of photopolymeric materials, the process makes it possible to create multimaterial combinations with high resolution and accuracy. It is commonly used for rapid prototyping as it is able to reproduce and recreate several material qualities, from hard plastics to soft elastomers.

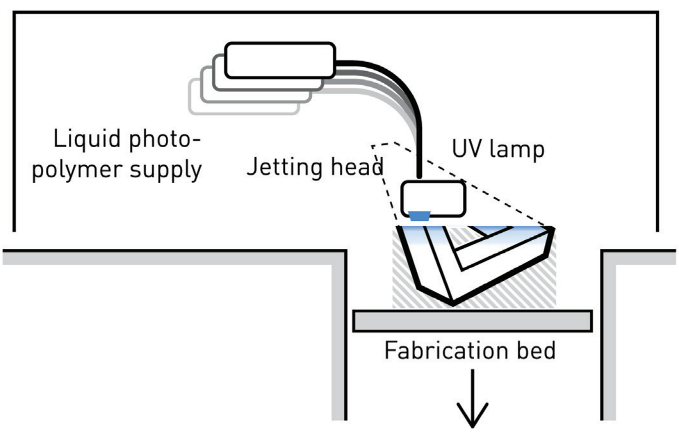


Figure A.8 After depositing droplets of a photopolymer through a print head, a UV lamp solidifies each layer of material.

Much like an inkjet printer deposits its inks onto a piece of paper, the PolyJet printer leaves droplets of photopolymeric liquids, which are then cured by UV light (Fig. A.8). Whereas ordinary paper printers produce pixels of color, the PolyJet printer produces 3D units of material, known as voxels. Similar to an FDM printer, the PolyJet printer fabricates in a layerwise fashion in open space. Consequently, a certain amount of soluble support structure is deposited. Upon completion, the part is taken to a postprocessing chamber and the support is water-jetted away.

A.4.2.2 Design considerations of PolyJet printing

The PolyJet process is able to reproduce high-resolution surfaces, with layer heights down to 16micron. This makes it possible to create models with a high degree of details, as well as having high mechanical properties.

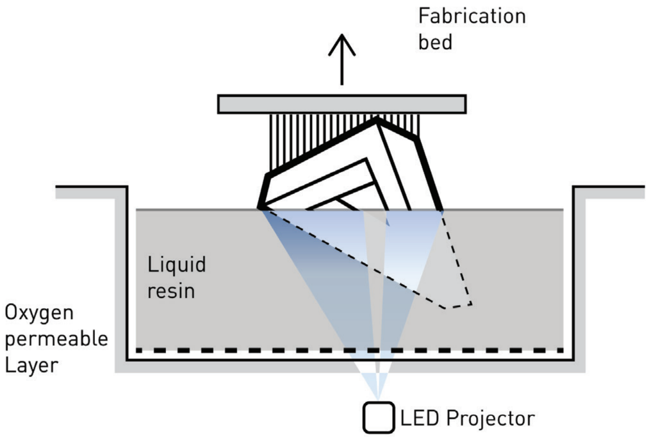
A.4.2.3 Materials in the PolyJet process

PolyJet technology is unique for its ability to offer a wide range of materials, in combination with each other, or even with gradient properties. Available materials range from rigid general prototyping materials to rubber-like elastomers to ABS- or polypropylene-like materials to translucent plastics. Recent advances in material and process technology have also made it possible to print in a wide scale of colors.

A.4.3 SLA-DLP

A.4.3.1 SLA-DLP background and process

Similar to SLA, the stereolithography digital light processing (SLA-DLP) process uses a liquid photopolymer as the fabrication material. Whereas most SLA processes use a single laser source for curing the photopolymer liquid, SLA-DLP processes cure entire cross sections at a time using DLP projectors, similar to that of a home cinema. The principle was first used by Envisiontec in the early 2000s and has since evolved into technologies such as continuous layer interface production (CLIP), pioneered by Carbon 3D, which makes use of an oxygen-permeable layer between the resin tank and liquid. This enables the continuous curing of resin, which greatly speeds up the fabrication process.



The principle, which cures entire cross sections of photopolymeric material at a time, has both advantages and disadvantages in comparison to traditional SLA techniques. Firstly, it has the potential to speed up the fabrication process, as the single DLP light source cures entire cross sections at a time. The DLP projectors may also generate gradient light sources, making it possible to cure several layers with different light intensities. However, SLA-DLP relies on a DLP projector as the light source, which has to be mounted under the resin tank and takes up considerably more space than a desktop SLA printer.

A.4.3.2 Design considerations of SLA-DLP printing

SLA-DLP printers are typically capable of fabricating with layer thicknesses varying from 0.015 mm to 0.15 mm. The SLA-DLP printer is considered a process capable of producing high-resolution parts and producing surfaces of near-injection-molded quality. The process often requires additional support structures, which may require postprocessing. To minimize the amount of support structures needed, parts may be either tilted to minimize overhangs or specifically designed with angled overhangs. A common rule-of-thumb is to avoid overhangs of less than 30°.

A.4.3.3 Materials in the SLA-DLP

Much like the SLA process, SLA-DLP materials are available in a range of material qualities, from clear, translucent plastics to biocompatible dental materials. Most of the available technologies make use of proprietary materials.

A.5 Solid-Based Processes

The simplicity of solid-based processes has in many ways become the public symbol of how 3D printers work. Found in schools, libraries, and workshop environments, the desktop 3D printer relies on a continuous string of material filament, usually thermoplastic, which is heated up by a moving extruder head and deposited in a layerwise fashion onto a flat surface. As each cross section of the desired artifact is constructed, the extruder head moves to the next layer and continues to deposit material. The process continues until the desired artifact is fabricated.

Common technologies that make up solid-based processes are fused deposition modeling (FDM) and fused filament fabrication (FFF), which all deposit material through an extruder. Similar principles, such as rapid plasma deposition (RPD), developed by Norsk Titanium, rely on additional subtractive forming methods to create precision details, as the deposited material consists of titanium in a plasma state. Other processes, such as Solidscape, deliver droplets of heated wax, which are then subtractively formed in order to create high-detailed positive shapes for lost-wax casting. While all the aforementioned processes involve smaller units of solid-based material being deposited, the laminated object manufacturing (LOM) process relies on sheets of material being cut and glued together.

A.5.1 Filament Deposition Modeling / Fused Filament Fabrication

A.5.1.1 FDM/FFF background and process

The concept of FDM was initially developed by Scott Crump, who was awarded the initial patent in 1992. In the years that followed, Stratasys turned the technology into a series of 3D printers, such as the Dimension and Fortus for industrial purposes. Soon after the key patent expired in 2009 [2], the marked for low-cost, open-source 3D printers proliferated as low-cost electronics and simple mechanical solutions made them feasible. The term "fused filament fabrication" (FFF) was coined by the RepRap project, whose goal is to openly develop a low-cost 3D printer that can print most of its own components [1].

Whereas industrial FDM processes use proprietary components such as material cartridges, dual extruders, and enclosed heating chambers, most of the FDM/FFF 3D printers are open structures made by off-the-shelf components. They both operate by extruding molten material through a heated nozzle, which is mounted onto a moving head. The extruder head usually moves on a flat plate (*X* and *Y* dimensions), depositing its material onto a fabrication bed. Upon the completion of each layer, the heated nozzle moves in relation to the fabrication bed (in the *Z* dimension), gradually forming cross sections of the artefact (Fig. A.9).

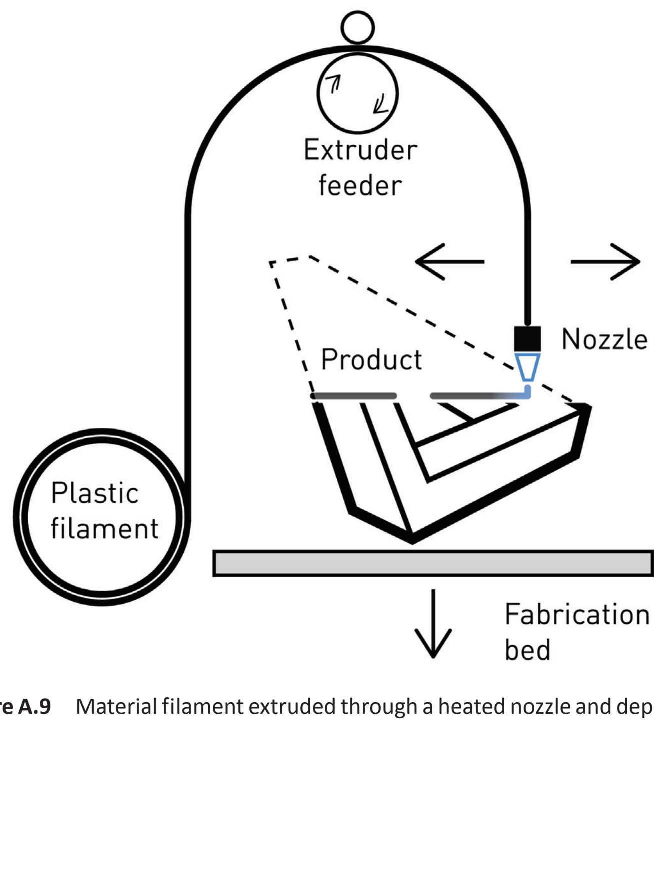


Figure A.9 Material filament extruded through a heated nozzle and deposited.

A.5.1.2 Design considerations of FDM/FFF printing

The FDM/FFF process operates in open air, which puts constraints on the design that is to be manufactured. A common rule-of-thumb is to avoid cantilevers that exceed 45° from the build plate when operating without support. Most industrial-grade printers utilize a dual-nozzle setup, with building material being extruded through one nozzle and a soluble support material through the other. Single-material, desktop-grade printers use the building material as support material, which has to be removed manually after the fabrication process. Free-floating enclosed parts are difficult to make as the process operates in open air.

As with most other fabrication processes, the FDM/FFF process operates in a layerwise fashion. Layer by layer of material is deposited with common layer thicknesses varying from 0.1 mm to 0.5 mm, depending on the nozzle diameter. The layers that make up the artifact are often visible, especially on near-horizontal sloped surfaces.

Depending on the material choice, fabricated objects are seldom isotropic; they are often significantly stronger in the direction of the fabrication bed. This is due to the fact that continuous strings are fused onto each other, with the bond between layers being significantly weaker, depending on the use of material. In some cases the fabricated object may even be water permeable.

A.5.1.3 Materials in the FDM/FFF process

Two convincing aspects of most solid-based processes are the low cost and wide range of materials available for FDM/FFF processes. ABS, a common thermoplastic, has traditionally been the material of choice as the material is well suited for extrusion. Many low-cost FFF printers prefer to operate with PLA, an organic thermoplastic, as the material allows for fabrication without the need for a heated chamber. Recent material developments have made it possible to fabricate with polymers such as PET, commonly found in soda bottles, as well as Nylon materials. A wide variety of blended materials such as PLA or PET mixed with bamboo, brass, copper, and carbon fiber are becoming popular among users of 3D desktop printers, because of the aesthetical and material qualities they offer. Conductive materials for capacitive touch applications are also available.

A.5.2 Laminated Object Fabrication

A.5.2.1 LOM background and process

LOM emerged as a method of fabricating prototypes using rolls of paper that were cut and glued in a layerwise fashion (Fig. A.10). The initial process, developed by Helisys, struggled with maintenance and technological issues [10]. The paper-based artifacts were best made as solid, thick-walled parts, while the industry was increasingly demanding prototyping tools for functional and detailed models. Although Helisys folded, more recent companies such as Mcor Technologies have met with success using the process. By using standard A4 sheets in combination with a desktop inkjet printer, models can be made both economically and in color.

Although the process principally uses rolls of paper, more recent technologies such as the Mcor Iris place layers of standard 80 gsm A4 sheets on top of each other, which are glued and cut, eventually forming the model. When making color models, each A4 sheet is preprinted with a color inkjet printer before being placed onto the fabrication bed.

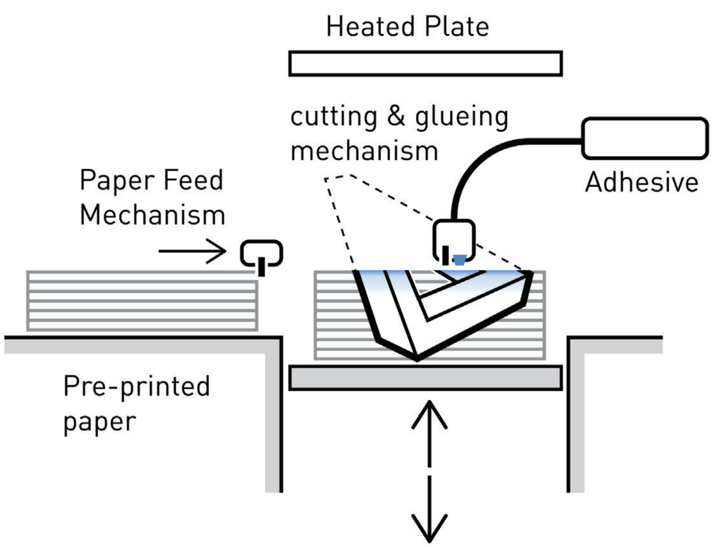


Figure A.10 Sheets of paper are cut, glued, and heated, layer by layer.

A.5.2.2 Design considerations of LOM printing

A minimum wall thickness of 4 mm should be considered, providing enough area for proper glue adhesion. Parts will have less strength in the *Z* direction relative to *X* and *Y*, although cohesive strength can be increased by applying glues or other adhesives.

A.5.2.3 Materials in the LOM process

As the principal material in use is paper, postprocessing, such as cutting and drilling, is easy. The LOM process is not typically used for functional parts.

A.5.3 Rapid Plasma Deposition

A.5.3.1 RPD background and process

Titanium alloys are traditionally known for being difficult to machine. In addition, 90% of the material may need to be cut away, making the forming of titanium both time consuming and costly. By combining both additive and subtractive forming principles, RPD is able to manufacture end-use parts from specialist metals such as aerospace-grade titanium. The technology, pioneered by Norsk Titanium, fabricates a near-net shape, which is up to 80% complete, before surface finishing and detailing with a CNC mill (Fig. A.11). The process uses both less energy and less time compared to conventional milling of billets. The technology is able to deposit 6 kg of titanium per hour and is aimed toward building larger structural components [6].

Using the principles of plasma arc heating, titanium wire is heated and deposited into a substrate in a cloud of argon gas. The near-net shape is fabricated in a layerwise fashion. Continuous process monitoring ensures that the layers consist of seamless, homogeneous structures. The deposition bead, which is approximately 8 mm in width, is then milled to provide a smooth surface.

A.5.3.2 Design considerations of RPD printing

The technology is developed for larger structural components, up to 900 × 600 × 300 mm^3 in size, and is not optimized to produce small embossed or debossed details. Being a composite fabrication process, RPD can reproduce any shape rising vertically out from the substrate. The technology has no capacity for creating support structures. Surfaces inclining from the substrate are limited to 30°.

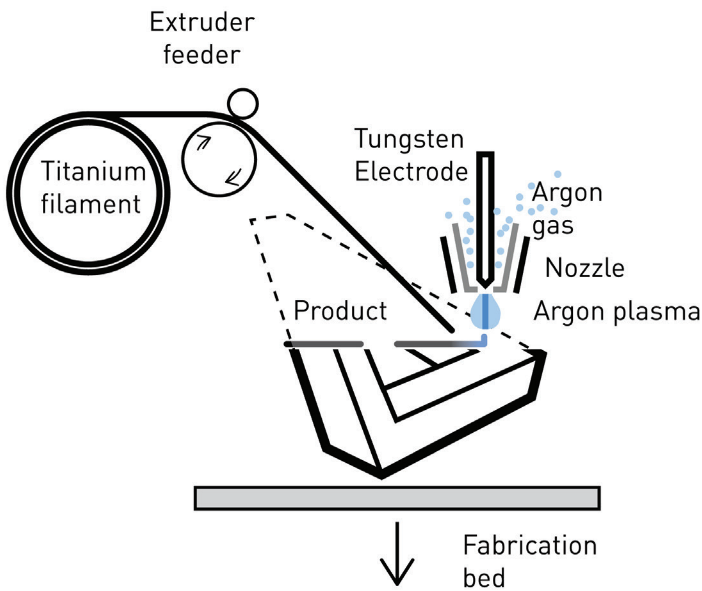


Figure A.11 A near-net shape is fabricated by fusing titanium filament through exposure to argon plasma before it is milled and surface finished with a CNC mill.

A.5.3.3 Materials in the RPD process

The technology is primarily developed around the use of titanium. The material exists in several alloys, Ti-6Al-4V being a common specification. It is known for its ability to be resistant to corrosion in seawater and chlorine. A low density and high strength ratio, fatigue resistance, resistance to heat creep, and biocompatibility make titanium sought after in as diverse circumstances as jet engines, prosthetics, medical implants, and bicycle frames.

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Chapter 4

The Impact of Making: Investigating the Role of the 3D Printer in Design Prototyping

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4.1 Introduction

4.1.1 Prototyping as Design Development

A common feature in almost any design endeavor is its involvement in the making of various forms of models and prototypes. These prototypes are often described as the articulations, or manifestations, of ideas and concepts. The making of prototypes and models is an integrated part of many different creative disciplines, both in architecture and in design. However, the ways in which these prototypes are made, and with which tools, differ considerably. An architectural prototype is described by Runberger [42] as "an object of continuous investigation," both malleable and performative, that

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allows the authors to cocreate and iterate on a physical design. In designing digital, screen-based experiences, the need for prototyping, as explained by Houde and Hill [2], is a crucial and complex task. It may involve the creation of both interactive slide shows and physical foam-core models. In product design, the importance of physical prototyping is particularity evident in the fact that end results are often physical.

While the discussion of attributes, skill, and tools in prototyping remains relevant, the question of what prototypes and artifacts actually do has been of continued interest among design researchers. Houde and Hill [22] proposed a model that tracked prototypes within three dimensions: the artifact's role in a user's life, the look and feel of the artifact, and the implementation of it. Buchenau and Suri [7] furthered the argument of prototypes as experiential components that exist in order for a design to be understood, explored, and communicated. Further unpacking the notion of prototypes as an integrated part of product development, Lim et al. [32] elaborated a theoretical framework of prototyping "as a vessel for traversing a design space" or as "purposefully formed manifestations of design ideas." Their description of design activity, which can be seen as reflective rather than prescriptive, situates the prototype as a filter and qualitative manifestation of a particular design space (Fig. 4.1).

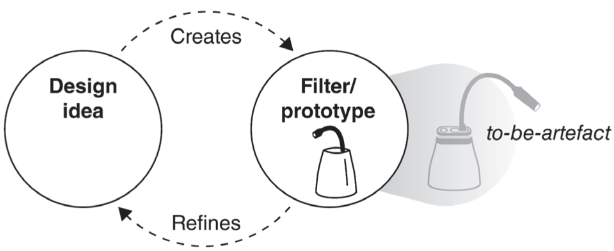

Figure 4.1 Prototypes act as filters or manifestations of a design idea. Illustration: William Kempton.

4.1.2 Making as a Critical Practice

While many of these studies emphasize the roles artifacts play as representations and filters of design intentions, other scholarly contributions emphasize making as an act for critical inquiry. Matt

Ratto (2011) coined the term "critical making" as a mode of inquiry that extends theory into physical space [38]. Ratto's theoretical framework for making emphasizes critique and exploration in order to understand new concepts, rather than solving them with technically sophisticated prototypes. Critical making can be seen as a juxtaposition of critical thinking, which is based on linguistic and theoretical expression, with tacit acts of making artifacts. In recent studies, Ratto and Ree [39] investigated 3D printing as a fluid technological phenomenon that has great implications for materializing digital and physical convergences. Critical making being a potentially socially transformative technology, Ratto and Ree employ critical making workshops with layperson participants. This allows these design researchers to delve into topics such as literacy (the need for development of skills in a new digital economy), infrastructure (citizen involvement through making), and legislation (the potentials and ramifications of collaborative, "open-source" sharing of designs) [39].

4.1.3 Outline

In this chapter I investigate the emerging use of digital fabrication from the perspective of product design practice. 3D printing, in particular, has been primarily seen as a prototyping tool, leading to the name "rapid prototyping" (RP). As a collection of technologies for reproducing and generating physical artifacts, based on a digital blueprint [21], the emerging trend in 3D printing is a gradually movement toward production of usable artifacts, due to the gradual improvement of material properties, affordability, and speed [13]. To understand the potentiality of 3D printing as a tool for prototyping ideas and concepts, while at the same time as a platform for additive manufacturing (AM), provides the central problematic in my research. I therefore ask, "How is the emerging, expert use of digital fabrication providing new models for product conceptualization?"

This article ties into theories and discussions from product design that relate to emerging craft and practice. Whether it's labeled a prototype, model, or a mock-up, the act of making representations is an inherently important process for understanding and solving complex issues. Arguably, these acts are something designers have always been doing. What this article attempts to analyze is the developing use of 3D printing in the systematic design process. This rationale for investigating the 3D printer's role in design prototyping is to understand how it might complement the evolutionary ways in which design is being developed.

My chapter is separated into six main sections. The introduction outlines various motivations for making, with artifacts and representations, in a product-oriented design process. This is then tied onto emerging knowledge in the use of 3D printing as a developmental and production tool. Following a further discussion on the role of representations in design prototyping, I discuss in Section 4.5 how expert designers work with 3D printing, seen from the case of the development of the SunBell lamp. I then present an existing model of product design prototyping, which attempts to organize the role of design representations within design development processes. This model is then further elaborated in Section 4.6 of the article to accommodate the developing role of 3D printing as an integrated tool for development and material production.

4.1.4 Methods

As mentioned earlier, the making of artifacts and representations is often integral in the developmental process of many design practitioners. While artifacts can be described as vessels, filters, or manifestations of a design space [32], they are often complemented by methods and tools for observation and analysis. To understand latent user needs, contexts, and scenarios, designers are increasingly involved in mapping and research activities, such as gigamapping [46] and ethnographic field research [47]. As a result, the developmental process of design practice can be seen as "oscillating between poles of Real versus Abstract and Understanding versus Making" [28].

In contrast, the methods I have used to understand the contemporary phenomenon of how digital fabrication tools play a role for product conceptualization borrows from social science research methods such as case studies [51] and qualitative interviews [29]. These methods of inquiry not only serve to explore the phenomenon in question but also allow me to understand and provide qualitative descriptions of their "designerly" approaches [10].

As a designer and researcher, I also take on an observational, ethnographic role, which also has its roots in the social sciences [37, 43]. This can be likened to practices such as field research, which seek to understand practices of everyday life through a firsthand view.

As a way of addressing the phenomena of design and architecture practices as a continuous dialog between themselves and the situations in which they find themselves, Donald Schön (1983) introduced the notions of reflection-in-action and reflection-on-action [44]. Briefly put, these notions describe the way in which practitioners of design are found to reorganize their steps within a particular making process as they gather new knowledge of a situation. The designer reflects in action on the situation "talking back" to him or her, which leads the designer to form yet new strategies and moves [44].

Although the focus of my attention lies in observing and reflecting upon the developmental practices of other designers, my observational, ethnographic approach is influenced by my focus as a researcher and as a designer. Extending Schön's notion of reflection-on-action, which emphasizes the revisiting of performed actions, I combine the knowledge that is obtained by me as well as the subjects of my observation to gain insight into the role of the 3D printer in design prototyping.

This chapter forms a part of my ongoing article-based PhD design research project [41], which centers on emerging design practices in digital fabrication. Because of the wide-ranging involvement in digital fabrication by many different social groups, the role of this book chapter is to investigate the contemporary practices of expert designers.

4.2 Background

4.2.1 From Rapid Prototyping to Additive Manufacturing

The emerging roles and potentialities of 3D printing are increasingly discussed in the popular media, spanning from an economical viewpoint [49] to perspectives on sustainability [31]. Because of the increased availability of 3D printing technology both for personal use as well as through services, digital fabrication tools and technologies can be seen as a distributer of personalized material production and even carriers of cultural expression.

Throughout the 1970s and the 1980s, the advancement of computing power and development of computer-aided design (CAD) applications, which made it possible to draft and draw on a screen, made it possible for a wide range of industries to engage in a new, digital material domain. Although initially used by automotive, naval, and aerospace industries, the use of CAD has had a profound impact on design development, particularly in integrating, modeling, and evaluating design ideas [50].

The earliest technologies for fabricating digital objects with 3D printing came with the invention of stereolithography by Charles Hull [23]. This gave way to the first era of 3D printing, which centered on making prototypes and models for product development in professional industry. “Rapid prototyping,” as the technologies were initially labeled, was revolutionary in that it made it possible to make multiple, precise replications of digital models that had been designed in CAD applications. Whereas the traditional way of making prototypes had been through hand work by skilled craftsmen, RP allowed product developers to make accurate prototypes in a rapid fashion [35].

The role of 3D printing in a product development process can be divided into three separate categories: the making of artifacts as representations for a concept, idea, or function; for making as a way of making tools for facilitating the making process; and lastly, as a means of manufacturing as artifacts. The last is of particular interest as digital fabrication technologies are increasing in quality, offering, and speed, making it possible to make usable, functional artifacts. The term “additive manufacturing,” which sees the technology as a platform for manufacturing, is of interest for engineering-centered research [17], as well as in product design. It also suits designers who look at new means of manufacturing, as well as potential users, as a range of new possibilities for materialization are opening up.

Some of the potentialities of AM include mass customization [36], the tailoring of mass-produced artifacts to each person’s preference, and the concept of enhanced design [24], where AM acts as an alternative for conventional manufacturing methods (such as injection molding) by improving the consolidation of parts, minimizing labor, and providing improved functionality.

4.2.2 Ubiquity and Stratification of 3D Printing

There is a clear demarcation between a broader and growing social interest in 3D printing and the expiry in 2009 of major 3D printing patents [12]. Of note is the RepRap movement, initiated by Adrian Bowyer, which seeks to develop open-source 3D printers for hobbyists. The movement is motivated by the idea that "the self-copying rapid-prototyping machine will allow people to manufacture for themselves many of the things they want, including the machine that does the manufacturing" [6]. Although the open-source RepRap movement has inspired much of the initial interest in developing consumer-grade 3D printers, it is often overshadowed by a plethora of commercial fabrication devices [4], online RP services such as shapeways.com, and user-friendly design programs [18]. On the basis of these continuously improving technological offerings that relate to digital fabrication, it is tempting to think that 3D printing will become a ubiquitous tool. This is also seen in comparison to the development of personal computing devices that have steadily moved from being stationary objects to laptops, tablets, and handheld smartphone devices.

In discussions on ubiquity and 3D printing for children, Eisenberg [14] discusses the importance of considering personal, digital fabrication as something more than a desktop object, much like the computational devices we carry in our pockets. Central to his critique of incorporating digital fabrication into an educational setting is to offer children "an experience of self-directed construction" [14]. This is seen in contrast to his view of children's experience of the web—with easy access to entertainment, online shopping, and even lectures—as an increasingly consumptive space.

From a multidisciplinary standpoint, Robert Ree [40] sees the idea of ubiquitous 3D printing as a misconception. He argues that because 3D printing cuts across several disciplinary boundaries, its purpose is stratified across different uses. Ree exemplifies this through a series of contexts and from an academic point of view, from which 3D printing can be utilized to teach people to open the "black box" of technologies, to that of a social galvanizer for collaborating on material investigation [40].

4.2.3 Contexts for Additive Making

The arguments advanced by Ree and Eisenberg point to a need to understand 3D printing as an emerging technological tool within a specific environment. As I am to understand how expert practices in product design are making use of digital fabrication, I next continue my discussion by referring to explorative use of 3D printing for materializing digital information by the design company Skrekkøgle.

Figure 4.2 A rich design space where tools, materials, technology, and methods meet. Favorable combinations of straps, plastic enclosures, and even sensory feedback are found through the method of trial and error, material exploration, and experiencing a messy but necessary process. At the Skrekkøgle offices in Oslo, Norway. Photo: William Kempton.

Leather straps, milled aluminum, electrical wiring, sensors, doodles, and 3D-printed watch strap buckles are spread around a large table (Fig. 4.2). Across the table, at the other end of the room, a silicone mold is seen revealing the negative shape of a figurine, while snippets of code are being transferred to a blinking Arduino board. Almost every square centimeter of available space in the room seems the victim of some kind of making experiment. The space, situated in a back alley in Oslo's Grünerløkka district, is the home of Skrekkøgle, a multidisciplinary design office run by Theo Tveterås and Lars

Vedeler. They have come to represent a generation of designers who embrace digital and physical materials through their emerging use of technology, as well as the things that are literally coming out of their 3D printers.

The various artifacts on the table are the remains of what became Durr Alpha, a sensorial wristwatch the duo created in 2014. Durr refers to the shivering sensation the watch gives every five minutes as a way of indicating time. Alpha, referring to the maturing process of software development, in many ways encapsulates the state of the product, as it was made in a limited, completely hand-assembled edition. Using 3D printing services and simple prototyping electronics, Skrekkøgle was able to release the initial product to a public audience. “We learned so much about quality control and logistics from the project. From color dyeing the 3D printed plastics to configuring the code. As soon as we released the initial product we decided to make another, better iteration of it,” Lars says as he fondles an early prototype. The following year, the Durr Beta (Fig. 4.3) was released, this time incorporating a larger extent of external assembly, computer numerical control (CNC)-milled casings and custom printed circuit boards (PCBs) fitted onto a 3D-printed board. In many ways, the naming of the watch, Durr Alpha and Beta, symbolizes a convergence between the fluid development of software and the emergence of digital fabrication technologies, such as 3D printing.

Figure 4.3 The Durr Beta watch, featuring an aluminum case with SLS-printed internals and a leather strap. Photo: Skrekkøgle.

As the boundaries between digital and physical space draw closer together, both physically and metaphorically, for designers there open up both possibilities and implications for designing. One of the possible convergences of digital and physical materials, and extended by network connectivity, is hybrid artifacts, popularly labeled “Internet of Things” (IoT).

4.2.4 Hybrid Artifacts

The computational objects and artifacts that we interact with in our everyday lives—telephones, music devices, cameras, smart watches, and quantified-self devices—can be seen as blurring the intersection of analog materiality and digital information. Such devices are continuously enriched and upgraded through new technological offerings and features. However, their presence within larger communication networks and their continuous exchange and computation of data distort what Knutsen [26] calls the “spatial context” of static artifacts. Such IoT product hybrids can be seen as breaking the mold of traditional tools and interfaces. Rather than being confined to certain domains and purposes, hybrid devices can be seen as “complex articulations and assemblages of material and cultural domain” [26].

I align my notion of a hybrid artifact between product design and AM with Knutsen’s description of it as a complex assemblage of material and culture. Indeed, the material output of a digital fabrication process converges heavily between digital and physical space. As I later argue, an emerging kind of artifact— the releasetype—can be described as a hybrid artifact. It coexists as digital and physical material and comprises instances of an end product realized through AM. These artifacts are hybrid products in that they rely on interdisciplinary design competencies and processes in order to create the necessary design framework, which is adaptable by a digital interface. Such interfaces can already be seen in web-based self-services such as the NikeiD online custom shoe design service (Nike: nikeid.nike.com), which encourages creativity and allows customers to partake in codeveloping products [16].

4.2.5 Making Representations as a Way of Designing

Designers are concerned with making as a means of articulating and exploring their ideas and concepts. As with almost every design practice, such as publishing; jewelry design; and industrial-, interaction-, and service design, working with representations, such as sketches, models, and prototypes, is vital to both developing and presenting concepts methodologically. These concepts may be as diverse in both complexity and form as templates for online magazines, a mood board for a collection of necklaces, or complex flowcharts and guidelines for a new pension reform. In industrial design, a concept is usually presented as a tangible artifact so that a 3D-printed scale model or a series of prototypes represents the tactile, compositional, functional, and aesthetical qualities of a design.

In craft production, the act of designing is tightly knit with the physical making of that object [45]. A pottery maker who is turning a piece of clay is gradually making up a form as he or she goes through a process. However, in industrial and contemporary design practice, the act of designing an object is separated from the making of it [11] as the object is designed for someone else. The core goal of the industrial designer is, therefore, to provide a rich description of a design before it is produced. This entails how the product is used, how it looks, and how its manufactured. When designing a children's chair or a desk lamp, the industrial designer is not only concerned with how comfortable the chair is to sit in or if the lamp falls in line with the taste of the perceived users of it. For a design to be successful, the product should be manufactured in a rational way; it has to comply with standards of the surrounding environment, as well as hopefully fill a perceived market need.

4.3 Prototypes and Design Representations

The making of representations is arguably a vital part of the process of developing products. They encompass everything from initial sketches to elaborate drawings, models, and prototypes. In addition to facilitating the evolution of a design brief to a design solution, representations such as models and sketches act as modes of communication between the involved actors of a design process—between an industrial designer and an engineer, between the designer and the manufacturer, or even between users and the designer. In a broader view, mock-ups or cultural probes may even be used to critically engage with users, as opposed to gaining concrete solutions to user needs [5].

A holistic perspective of visual design representations (VDRs) is offered by Pei et al. [34] as a means of enhancing the communication between the involved actors, particularly emphasizing industrial designers and engineers. The authors point to the inherent cultural differences between thinking styles and values of these two disciplines as leading to misinterpretation. For instance, an industrial designer might focus on the aesthetical attributes of a sketch, while an engineering designer may use sketching as a means of solving technical details. Similarly, when making models an industrial designer might consider usability aspects, while an engineering designer might make models to evaluate mechanical principles and production feasibility.

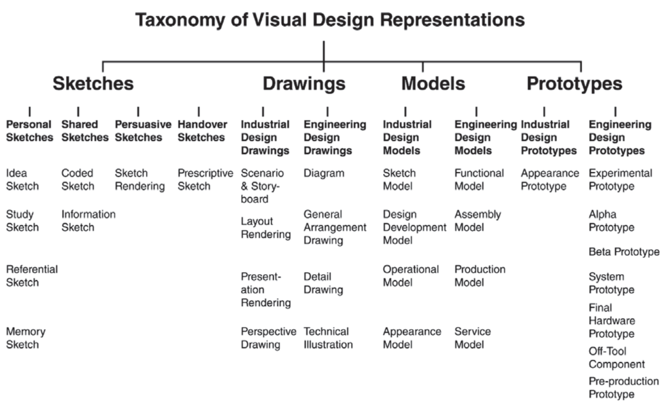

Figure 4.4 Taxonomy of design representations (Pei et al., 2011, p. 69).

The resulting taxonomy can be seen as a generic timeline, in terms of both complexity (a sketch is usually less time consuming than making a physical model) as well as evaluative purposes—an appearance model is probably easier to comprehend than a drawing of it. The VDRs (Fig. 4.4) are divided into four main types: sketches, drawings, models, and prototypes. The chart is heavily influenced by the opposing cultures of industrial designers and engineers, as is seen by the continuous comparison of the two in each type. Although it doesn't specifically refer to any particular tools for making, such as the use of hand tools or digital fabrication, it provides a clearer image of the landscape of representations in relation to the opposing disciplines.

4.4 The Changing Character of Design

Design practice varies across the various disciplines it encompasses. From engineering-driven design to fashion design, the processes that facilitate designed artifacts and outcomes intersect on several levels [30]. They often share a sensitivity toward relating and addressing users' needs in different ways, often referred to as user-centered design [1]. To address latent needs and provide satisfactory user experience, the process of design involves techniques for collecting data, observation, usability testing, and prototyping. The process of making products is necessarily a multidisciplinary one, and it is often formalized as organizational strategies.

Marketing departments, designers, investors, material experts, engineers, salespeople, and potential users are all actors in a complex web that makes up the process of product development and innovation. All these actors may perceive the act of developing products in different ways. This makes it necessary to formalize both the methods and strategies that comprise the process. Large corporations and design companies, such as Unilever and IDEO, are continuously refining these methods, strategies, and approaches in an attempt to be innovative and successful.

4.4.1 New Product Development

The overall managerial strategy of product development and innovation known as new product development (NPD) is concerned with transforming market needs into new products while emphasizing speed, flexibility, and on-time delivery [48]. The NPD strategy is generally described through a set of stages and gates [9], which typically involves discovery, idea scoping, building a business case, development, testing, and validation, before being launched. The various stages of the process call for multidisciplinary approaches, including that of marketing, engineering, and design [15].

The role of design is emphasized as conceptualizing and clarifying fuzzy or ill-defined problems (wicked problems), centered around the initial stages of the formalized NPD process, often described as the fuzzy front end [27] of design. Often seen as preceding the formal product development process [3], the fuzzy front end is handled by designers as they are skilled in transforming fuzzy problems into ideas and concepts.

As mentioned earlier, the user-centered approach requires designing practitioners to move among modes of looking, learning, asking, making, testing, evaluating, selecting, and communicating [33]. Because users often prove to have different needs and opinions, these modes of design development are often revisited in a cyclic fashion. Tools for facilitating parts of these processes, such as interviewing and observing users, are complemented by acts of making and testing, in order to further the developmental, iterative process. As technologies for 3D printing are becoming increasingly quicker, cheaper, and easier to use, so has their use in the process of making products.

The literature concerning NPD strategy often emphasizes the role of design as being in the initial, fuzzy stages of the developmental process. However, as the cases in the following sections elaborate, designers are increasingly enabled by digital fabrication to engage in product development that travels beyond the fuzzy front end.

Figure 4.5 illustrates how the modes of design practice—looking, testing, and communicating—can be viewed in relation to the multidisciplinary view of NPD. It suggests than rather than being confined to the initial fuzzy front end of NPD, design practices are in fact integrated into the entire developmental process of making new products.

How then are designers actually using digital fabrication to facilitate their work? Through two cases—the SunBell portable lamp and the DF1 ski pole grip—I will attempt to unpack the way 3D printing tools are involved in the design process, as well as provide a contextual frame of what role physical design representations take.

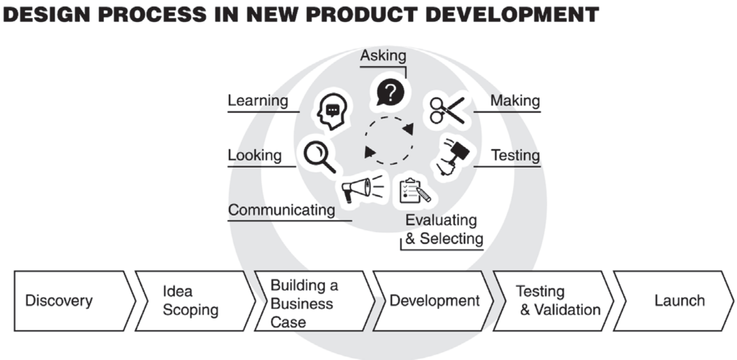

Figure 4.5 The design process within new product development is iterative and affects more than just the initial fuzzy parts of the process. Interpreted from Milton and Rodgers (2013) and Cooper (2011).

4.5 Situating AM Prototypes within Design Practice

4.5.1 Developmental Prototypes

I now turn to the case of the SunBell lamp, an award-winning portable solar-powered lamp with a USB phone charger. It is designed by the Norwegian design firm K8 and intended for off-grid use by the roughly a billion people that rely on hazardous kerosene lamps to provide lighting.

The SunBell case provides us with a context for the use of models, artifacts, and prototypes within a product design development process. While the end product is manufactured with conventional mass production techniques, such as plastic injection molding, AM tools takes up multiple roles throughout. It can be seen in the making of models as representations, through early conceptualizations of the lamp product, allowing the designers to negotiate functionality, usability, and shape. AM also acts as a tool for manufacturing, where it produces patterns for polyurethane (PUR) casting.

Marius Andresen, the founder of K8, saw the need to create a versatile sun-powered lamp that could meet a series of different lighting needs. While attending a workshop at the “Beyond Risør” event in Risør, in southern Norway, the participants were challenged with making lighting solutions based on various topics. K8 quickly decided on developing a lighting solution for replacing the hazardous kerosene lamps commonly found in less developed regions. Since its initial presentation at the lighting workshop in southern Norway, the initial mock-up has seen 4500 hours of research and development. The product is now sold commercially as well as through UNHCR incentives to countries such as the Philippines, Cameroon, Yemen, Sudan, Kenya, and Lebanon.

The entire process of developing the lamp, from early concepts to making functional prototypes and user-testing them, was conducted by K8. Much of this work is typically performed by the industrial designer, resulting in a set of functional and aesthetical models, accompanied by some guidelines and initial feedback. This is then presented to the client or manufacturer. This was not the case for K8, as the company itself had stakes in the project. After presenting the product concept at various design festivals, K8 found collaborating partners and created a dedicated company called Bright Products. With K8 as the developing entity behind Bright, investment for further development was found through private funding, corporate funding, as well as crowdfunding.

4.5.2 Initial Concept and Maturation of the SunBell Lamp

The SunBell project has been running since 2009, with the first batch of products delivered in 2014. Over a span of five years the product has gradually evolved in terms of composition and functionality.

The first concept of the SunBell (Fig. 4.6), composed out of simple IKEA parts, was made in April 2010 and featured an upside-down bowl with a penlight attached to it. The flexible goose neck, with the light in one end and a battery in the other, formed the principal structure of the product. In the following months, the basic concept with the flexible lighting source and the containing light-diffusing shade evolved into a basic operational model. Still using the IKEA hardware for the lighting and electronics, models gradually adapted to the new design. Using the in-house fused deposition modeling (FDM) 3D printer at K8, a new shape was made (Fig. 4.7) of the lampshade, allowing them to negotiate usability, functional components, and form giving.

Figure 4.6 The archetypal form of the lamp, made from IKEA components. Photo: K8.

"From an early stage we were making prototypes. From [the initial prototypes] we started to test out if we had enough space for the technological components, batteries, lighting, connectors and how the functionality fit with the overall concept," said Olivier Butstraen, who has been working with the SunBell project since the early conceptual stages. He is looking through a series of boxes containing prototypes and models, attempting to find the initial 3D-printed prototypes. This was not an easy find, considering all the broken pieces, artifacts taped together, and electronics partially assembled.

Figure 4.7 Initial negotiation of usability, functionality, and shape with initial rapid prototypes made with the in-house FDM 3D printer. Photo: K8.

A year after the initial workshop was held, K8 presented its first functional iteration of the SunBell lamp, as seen in Fig. 4.8. The initial product is entirely 3D-printed by their in-house FDM 3D printer. As the printer was only capable of creating rough models, they were painted and polished to simulate the materiality of injection-molded parts.

Figure 4.8 Functional prototypes of the SunBell presented at Beyond Risør in 2010. Photo: K8.

"At [the] prototype level we prioritized aesthetics and overall functionality [from a user perspective], more than considering the limitations of manufacturing. [The reason for] making the model was to show the concept and get feedback on it. So there was no need to solve technical details. In any way, the product was sanded down and painted," said Olivier. After being presented at the Beyond Risør festival and the establishment of the company Bright, the product was presented at events such as the Common Pitch in Canada, which the SunBell project won. The SunBell prototype gradually matured, although the overall shape and functionality were at this point set. "In many ways we worked ourselves inwards, as we started to get in contact with electronics experts, suppliers and manufacturers. But I am sure if you compared the silhouettes of all the models from day one to the mass-produced product you would see slight variations," remarked Olivier.

In 2012 a series of beta products were taken to Bangladesh, Kenya, and Tanzania for user testing. As eight models were planned for the trips, it was quickly decided to make a small series of products using PUR casting. Using the in-house 3D printer would simply be too much work. Instead, a series of silicone molds, one for each part of the lamp, was made using a high-resolution Objet printer to facilitate the making of molding tools for resin casting, as seen in

Fig. 4.9A. Once molded, the plastic parts were lacquered (Fig. 4.9B) in order to imitate the desired color of the product-to-be.

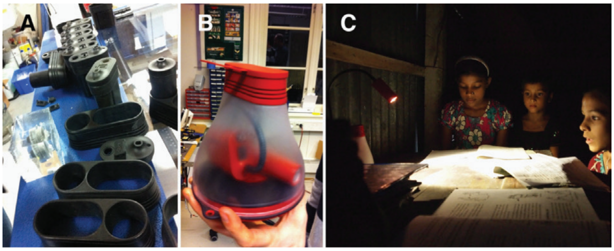

Figure 4.9 (A) Black polyurethane models that were molded for user testing. (B) After molding the models were lacquered in order to imitate the desired color of the product-to-be. (C) Field testing of the SunBell prototype in Bangladesh, Tanzania, and Kenya. Photo: K8.

The beta products proved to have two purposes—for gaining insight through field studies and for proving the marketability of the product. While the principal functionality and overall shape proved to be satisfactory in the field study, they gave the designers insight into potentials for improvement. Among others the integrated USB port would easily collect dust and could hinder the successful charging of a mobile phone. Observations such as this were then documented and would later help the designers in reiterating specific parts of the design before it went into mass production.

4.6 Design Representations and Multitypes in Product Design

In line with established development strategies, Capjon [8] introduced the concept of rapid multityping (Fig. 4.10), as opposed to conventional RP and rapid tooling, as a way of providing richer and more appropriate definitions to making representations in the development process. The approach is also contextualized in research by Killi, which develops a product-design-centered perspective and model on AM [24]. Capjon's vocabulary is heavily influenced by the emerging use of 3D printing as a strategy for constructing design representations and emphasizes the collaborative nature of designing new products.

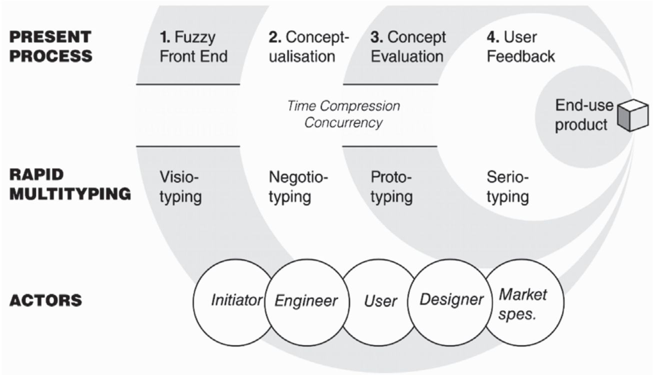

Figure 4.10 A redrawn model of multitypes. Redrawn illustration: William Kempton.

The rapid multityping models are distinct and refer to particular stages in the design process. Visiotyping is introduced as the process of developing visiotypes, initial mock-ups at the fuzzy front end of a design project. Negotiotyping deals with the actual conceptualization phase, with the relevant actors making a series of incremental negotiotypes for materializing mental imagery. The established notion of prototyping refers to the stage of concept evaluation, where prototypes are gradually introduced to other actors and stakeholders. Seriotyping emphasizes the functional and adaptive aspects of the user feedback phase, with seriotypes facilitating the event. No particular definition is provided for the process of manufacturing end-user products, although Capjon indicates the potentials of AM where conventional tooling is prohibitive or the possibilities of AM make it feasible.

The two models (Figs. 4.4 and 4.10) present contrasting views and taxonomies of VDRs used by designers. While the taxonomy of Pei et al. [34] offers a grid-like, structured, and highly detailed view of all the most commonly used forms of design representations, the Capjon model is less structured and does not provide a clear understanding of what the visio-, negotio-, proto-, and seriotypes might actually contain. As seen in the linear development process figure of Capjon (Fig. 4.10), no clear description of the representations is given, other than their being at different stages of the development process. Little emphasis is also given in Capjon's model concerning user feedback after the design development process is concluded. As a design process draws to an end, the design project is simply handed over to another party and eventually made into a product. The model also does not provide any clear transitionary information. The final development phase simply transitions over to the product space.

4.6.1 Multitypes in Rapid Prototyping

Multitypes may be applied with respect to RP (Fig. 4.11). They are useful in helping us understand the relationships between various stages in the design process. This can be seen in two cases. The first refers to the SunBell case mentioned above, concerning conventional manufacturing techniques and RP. The second case, with Pivot, refers to the role of 3D printing as it extends from a product development process.

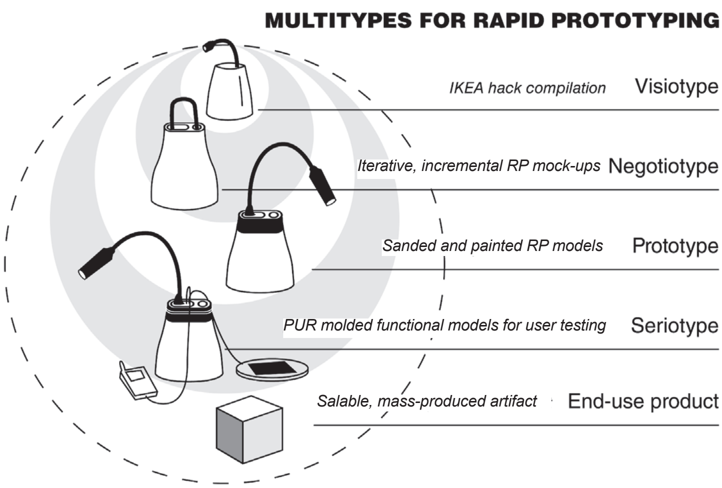

Figure 4.11 Multitypes in rapid prototyping. Illustration: William Kempton.

Case 1: SunBell

So far the SunBell case has provided us with a practical frame for the use of design representations within a design development process. The representations described in the SunBell case can be categorized within the multitypes as introduced by Capjon. The initial IKEA mock-up (Fig. 4.6), embodying the basic product functionality and composition, fits within the definition of a visiotype. The negotiotype, the early 3D-printed models using IKEA electronics, allowed the designers at K8 to refine the ergonomics of use and placement of hardware, as well as simulate the various lighting solutions. The conceptual model displayed at Beyond Risør embodies that of a prototype, as it represents the aesthetics and user functionality of the product-to-be. Lastly, the seriotype can be seen as the small-volume-production PUR lamps, which were used in field testing. From this case we can see that the multitypes are well defined and useful for the designers in their development process. As the actual product was intended for mass production by means of injection molding, the prototyping process culminated with the seriotype. Although minor alterations have since been made to the design of the lamp, (the lampshade has received an increased draft angle to enhance manufacturability), a redesign usually implies a reinvestment of costly manufacturing casting tools.

So far this case has described multityping for developing mass-produced artifacts, using 3D printing as a tool to facilitate RP. However, as 3D printing is entering a shift in paradigm, that is from RP to AM, we need to ask how multityping might be developed further. This may be done through reference to an experimental case that concerns the development of conceptual skiing grips by Pivot.

Case 2: Pivot

Pivot Industrial Design is a small design office located in Oslo, Norway. Its work spans from designing consumer and sporting goods to designing architectural installations. The company specializes in designing highly functional products and actively prototyping with 3D printers, laser cutters, and CNC mills in the development of them. “Everything is verified in our development process [before starting a manufacturing process],” exclaims Liam, one of the designers at Pivot.

The following case takes us through the story of developing a new generation of cross-country skiing poles. Pivot, in conjunction with Jørgen Weidemann Eriksen, found a need to improve the ski pole grip used by cross-country skiers for increasing the force output by 3%–4%. In principle, the grip tilts the user’s hand so that more force is transformed into the pole, making each stroke more effective. The design of the ski pole handle started off as any usual product development done by Pivot. An internal brief was created and initial prototypes were made. Conceptual mock-ups were initially made in playdough and foam, later advancing to gypsum 3D-printed models for more accurate visual form finding and ergonomic verification (Fig. 4.12). At a certain stage in the development process it became apparent that for optimal use of the product, several sizes had to be made available in order to fit different hand sizes. At the same time, a new prototyping material was available to them, PA11, a nylon material that surpassed the strength of other RP materials. While other RP prototypes proved short lived, the selective laser sintering (SLS)-produced PA11 had a superior material structure, enabling the designers to consider the possibility of using AM as an actual production technique.

Figure 4.12 Incremental development (left to right) through a series of models from the DF1 ski pole grip. Photo: Pivot Design.

According to Liam, "This basically allowed us to start thinking about completely new ways of encountering production limitations. No longer did we need to limit the design to even wall-thicknesses, or draft angles, [common considerations when designing for injection molding]." From the very beginning, the product was focused on a higher, more professional segment. Current ski pole grips are usually made of a combination of injection-molded plastics, as well as organic materials such as cork and leather. The 3D-printed PA11 was considered as a replacement for all the existing materials. However, unlike the existing ski pole grips, which were designed to fit a larger variety of hand sizes, the new grip would have to come in a variety of sizes to accommodate the ergonomic fit of different hand sizes.

"In the end the product never materialized for lack of external investment, but this could certainly change within a short time," Liam reflects. Although the product was never taken further than a conceptual stage, the designers at Pivot found a space for AM as a feasible method of production, with the potential for incorporating user-specific ergonomic fit.

4.7 Multityping in Additive Manufacturing

4.7.1 Popular Yet Professional?

The two cases mentioned above, the SunBell lamp and Pivot's ski pole grip, further a discussion on the implications of AM. While the first case illustrates development practices that integrate RP for making various forms of design representations, the second case advances the idea of extending RP equipment into a mode of production in order for Pivot to adapt to the end product to user-specific ergonomics.

Through online media libraries such as Netflix and Spotify, unfiltered access to culture and media content is being provided to a realm of users. Whereas traditional broadcasting, such as radio and TV channels, have been able to provide selected, curated content to the millions of viewers, the distribution of media through the Internet turns the ratio around: millions of varieties of music and film are available to each user. This scattering of the mass market to many niche markets is what Chris Anderson [2] refers to as the "Long Tail." The notion can also extend to physical contents, as online stores such as Amazon.com make new products and contents available to masses of people. Concerning the Long Tail of Things, 3D printing is envisioned as a distributed mechanism for manufacturing, with the desktop factory printer turning "bits into atoms in your own home" [2]. Although desktop 3D printing technologies are becoming quicker and more reliable, bringing these tools into domestic environments has its own implications. Aside from being restrictive in terms of size and choice of material (most desktop inkjet printer owners only have printers that support A4-size papers), the accompanying software tools for creating 3D models often require extensive practice. Many of these challenges can also be addressed through increased online collaboration. Online sharing platforms such as Thingiverse (thingiverse.com) already allow enthusiasts to share and codevelop products, while online video repositories such as YouTube (youtube.com) have become popular venues for online learning. The space in which the 3D printer is situated can also be virtual. Of note are popular 3D printing services such as Shapeways (shapeways.com) and 3DHubs (3dhubs.com), which give those who didn't previously own their own desktop fabricator distributed access to 3D printing services.

On consumerism and product innovation, von Hippel [20] discusses various modes of increased individualization. He clearly identifies a gap between users' diverse needs and the homogeneous offerings of mass-produced artifacts. This is partially identified though what he describes as lead user innovation, where engaged users, who are experiencing needs that will later be experienced by other users, actively and freely participate in organized innovation processes. Hippel [20] extends this into a "toolkit for user innovation and custom design," whose goal is to enable nonspecialist users to partake in the design of high-quality, manufacturable products that are customized to their specific needs.

4.7.2 Integrating AM in Product Design

From a design view we see that AM is in fact not just a replacement of current manufacturing techniques but the embodiment of a new way of thinking product design. Here, the processes of business development, engineering design, marketing, and operations are increasingly set closer together—as digital, physical, or hybrid products.

So far in this chapter I have attempted to create a holistic vision of how 3D printing affects the process of developing products. While the SunBell case related to a conventional paradigm of multityping, where the resulting models and artifacts were merely rapidly prototyped representations of a mass-produced artifact, the DF1 ski pole grip and Durr watch come to represent a different form of multityping. In design projects where conventional manufacturing is used, there is a large shift between latter stages of prototyping, seriotyping, and making the actual product, as investment costs for manufacturing tools are prohibitively high. However, in an AM paradigm, the step between the seriotype and a usable or commercial product can be seen as more fluid. Although new manufacturing tools may be used, or a supply chain needs be created, the investments costs for AM are considerably lower than conventional tool-based manufacturing. In addition, the customizable and enhanced aspects of AM products, such as products that take into account the materiality of AM, can be harnessed by online, digital services, such as digital-physical toolkits [19].

4.7.3 Toward the Releasetype

Unlike Knutsen's hybrid products [25], which are networked, connected devices with dynamic functions, the releasetype is dynamic in its digital form but fixated as it is physically reproduced. While the releasetype is available and accessible to people, it has a notion of temporality, always subject to change—in shape, content, and materiality. The releasetype is a result of a series of design representations made in a design development process, known as multitypes [8]. While other types—such as prototypes—are representations and models for internal product development, the releasetype lives in the open world, accessible to its end users. To further my argument of fluid, developmental transitions between material artifacts, I will first elaborate on the developmental practices of design and prototyping.

In AM products the transition from functional, usable seriotypes to the released product should be interrupted by a new classification of type—the releasetype. A releasetype is a digital/physical hybrid artifact consisting of a design framework and a user interface. As opposed to conventional product design where a typical design task is the shaping of a single artifact, the new design task becomes the forming of the releasetype solution space and interface. The releasetype is still the result of a systematic design development, incrementally matured through stages of visiotyping, negotiotyping, prototyping, and seriotyping. However, as a digital/physical product hybrid, the releasetype is tangible to its users primarily through an interface, where it can be extracted and fixed into physical space.

In Fig. 4.13, the releasetype is placed at the end of a succession of multitypes, to emphasize the iterative nature of design development. Whereas the preceding, physical multitypes can be seen as following a river fall cycle between the design development and stakeholders, the releasetype feedback loop is more immediate, converging between a physical and digital space.

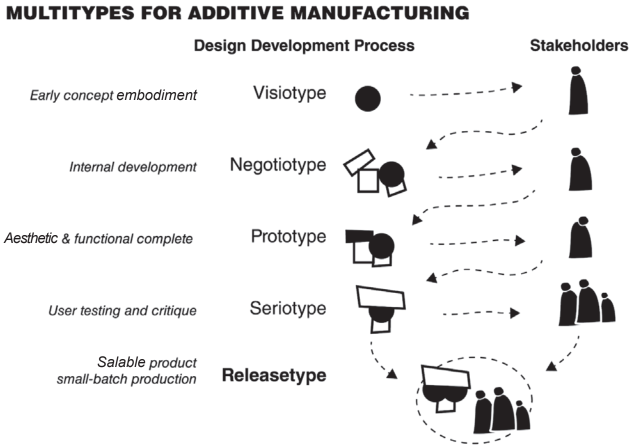

Figure 4.13 Multitypes for additive manufacturing. Illustration: William Kempton.

4.8 Conclusions

This chapter investigates the emerging use of digital fabrication from a viewpoint of product design practice. The question in focus is, How is the emerging, expert use of digital fabrication providing new models for product conceptualization? 3D printing, in particular, has been primarily seen as a prototyping tool, giving it the name "rapid prototyping." As a collection of technologies for reproducing physical artifacts, based on a digital blueprint [21], the emerging trend of 3D printing is gradually moving toward production of usable artifacts. This is due to the gradual improvement of material properties, affordability, and speed [13].

Earlier, I looked into how the Durr wristwatch, the SunBell lamp, and the ski pole grip function as some examples of how 3D printing is changing the landscape of additive product development. As one unbuckles the Durr watch, it is possible to see some of the new potentials and relationships between digital design space and product design. To account for such spaces for design in digital fabrication, I proposed the concept of releasetypes. This, I suggested, is a complement to the established use of prototypes in design inquiry and production. The introduction of releasetypes calls for a repositioning of the traditional sense of physical products into new kinds of digital/physical hybrids. However, unlike networked, connected hybrid products, the releasetypes are themselves digital design frameworks; they are manifested through physical materials when digitally fabricated. The introduction of the releasetype as a physical/digital hybrid product spurs on new discussions as to how it will change the role of design.

So why is this relevant for the designer? The purpose of the designer may be understood as expanding from balancing the broad variety of uses, use areas, and ways of using products to facilitating an increasingly cocreative space where both users and designers are able to work together. While 3D printing has been a part of design development for several decades, there is an increasing momentum in the development of AM and 3D printing, as it passes beyond professional use and into public, transdisciplinary access.

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PUBLICATION 4 – MEETING LEARNING CHALLENGES IN PRODUCT DESIGN EDUCATION WITH AND THROUGH ADDITIVE MANUFACTURING

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Meeting learning challenges in Product Design education with and through Additive Manufacturing

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ABSTRACT

Digital fabrication tools have been available to design students for the past 20 years. Tools such as 3D printers have been used to Rapid Prototype design concepts and representations, within product development and to imitate conventional manufacturing techniques. In the last decade, there has been an increase in interest surrounding Additive Manufacturing and a shift from 3D printing as prototyping to making end-use artefacts.With much core research still located in engineering frameworks, this article addresses perspectives from practice-based, qualitative inquiry into Product Design pedagogy. It does so through attention to specialist skills training, critical study and interpretation of the computational, material and socio-economic contexts and conditions surrounding digital fabrication. The pedagogical view on Additive Manufacturing we present incorporates both technical and socially oriented conceptualisations of design. We have attempted this through what we term an Additive Experiential Learning Model in the context of Product Design education. In the model we elaborate on a set of related mindsets: Designing *through* the technology and designing *with* the technology. While the former focuses on AM as a tool for realizing product ideas, the latter seeks to exploit and develop knowledge on the premise of the technology. The approaches offer pedagogical avenues and inspirations for industry in quests to use Additive Manufacturing and 3D printing in novel, experiential and practice-based ways.

Keywords: *Product Design education, digital fabrication, Additive Manufacturing, 3D printing, experiential learning, practice-based inquiry*

1. INTRODUCTION

Background

Digital fabrication technologies, such as laser cutters, 3D printers and CNC mills are becoming increasingly integrated in educational toolkits of design. As occurred with the appearance of CAD tools and computer labs in previous decades [1], digital fabrication tools are now seeing a strong presence in the studios and laboratories in design and architecture schools across the world.

Overarching pedagogical models of Design have also changed significantly in previous decades. A move took place from the integration of apprenticeship modes and theory building through the Bauhaus studio model, to increased attention to scientific methods in the Design Methods movement in the 1960s [2]. Design inquiry and related pedagogy has shifted further since then with contemporary design education located towards pragmatic theoretical frameworks [3], popularized through terms such as Design Thinking [4]. Due to the complex, and potentially contradictory outcomes of design intervention, designers are forced to move between iterative phases of *action* and *reflection*, a concept introduced by Donald Schön [5].

This movement corresponds with a large shift in focus from educating solely product-oriented industrial designers to a perspective of Design as a multi-disciplinary pursuit. Together with Product Design, Interaction Design and Service Design rely heavily on the use of digital technology for mediation, interaction and communication. While industrial design has to some degree always been concerned with understanding technology, such as the production of goods, developments in digital fabrication call for agile, experiential and critical learning approaches to Product Design education [6]. In particular, the appearance of digital fabrication tools, such as 3D printing, offer growing accessibility and flexibility enabled in terms of making design representations and rapid revisioning, as fixtures for other production methods, and as a novel production method [7]. In the context of Product Design education, digital fabrication technologies inspire renewed focus on understanding the hands-on application of tools, as well as continuing a critique of the development of digital fabrication technology as a whole within established approaches to learning to design with materials and tools in the context of situated, developmental learning and production-based inquiry. While our previous inquiries into AM [8] are indeed contextualised within emerging sites for learning, in aesthetics, branding and through developing AM-centric design methodologies, this article introduces a more critical discussion surrounding AM and Product Design learning.

The use of digital fabrication as a Rapid Prototyping tool has been around for decades, while its emerging role as an Additive Manufacturing (AM) technology is an area of interest for designers, architects and engineers. This interest also coincides with the evolution of smaller, desktop-friendly fabrication tools (Figure 1), which enable individuals and institutions with lesser resources to engage with digital fabrication. 3D printers, laser-cutters, CAD apps, 3D scanning software and CNC mills are becoming increasingly reliable and affordable. This widespread social popularization of digital fabrication, as well as the many technical promises of Additive Manufacturing, provides interest for new pedagogical models within product design education. However, in the context of Product Design pedagogy, our approach is a reflexive one: to explore the potentials of emerging technologies and tools while at the same time being careful, critical and constructive about their contexts of application and use. As with earlier commercial- and consumer-based practices and related discourses of digitalisation, there is a need to be wary of techno-determinist claims that digital fabrication provides.

Figure 1 – Desktop friendly fabrication tools are increasingly found in design studios and classrooms. Photo by William Lavatelli Kempton

Accordingly, we see a number of challenges for Product Design pedagogy that need to be addressed concerning of Product Design and digital fabrication. These are: 1) If Additive Manufacturing is to play a critical and constructive role within design, focus must be shifted from solely technique to a contextualisation of emerging technology in societal contexts; 2) How can we relate this to product design teaching on AM; and, 3) In what ways may design students learn and share their newfound knowledge on AM which does not only emphasise technique, but its roles within socially oriented contexts of use, making and exchange.

From these challenges we arrived at the two core research questions. The first of these addresses a wider need to understand and position a design based pedagogy of digital fabrication. This led us to the question: What are the emerging discourses connected to Additive Manufacturing? Building on a richer contextual framing of digital fabrication, informed by technical and sociotechnical research, as well as that of design based inquiry and related pedagogies of critical making and reflection, we developed a second question, centred on framing relations between teaching and learning. This question was articulated as follows: How can we elaborate on pedagogical models which allow prospective designers to understand and engage with digital fabrication?

A sociotechnical view of technology

A central argument to this article is that product design is continuously a part of the development and critique of technology. In relation to design, technology not only consists of the processes that designers engage with, it enables the use of skills and techniques for engaging with the world. The use and development of new technology is therefore an integral part of the designerly activities, from the fuzzy front end of design conceptualization, to the presentation of new design concepts.

From a social constructivist perspective, designers make up a particular group of relevant actors, alongside technology producers, tinkerers and business managers, which all take part in the development of 3D printing [9]. This social view of technology development focuses on the production of knowledge as opposed to the decontextualized technological production of artefacts. We employ such a view to our research on design and AM.

Motivation

This paper is based on research conducted at the Oslo School of Architecture and Design (AHO) for the past 22 years in the field of Additive Manufacturing (AM). Our AM research lab began through collaboration between local industry and AHO, where students were often involved in the research initiatives. One of the first artefacts ever made was a ski-pole basket. This item served as a visual prototype of a concept. It was expensive and fragile to produce, and handling the digital CAD file (designing, viewing and modifying) was a time-consuming process. The technology at the time was labelled *Rapid Prototyping*. Although the different technologies that existed in 1994 [10] have since improved, they are still basically addressing the same processes, with many of the same challenges. These relate to quality, speed and price.

As an adaption from a conference paper, presented at The 8th International Conference on Society and Information Technologies conference [11], this journal article draws further lineages from socio-technical developments on technology, as well as in emerging sites of design learning. Through these readings we intend to address both challenges and developments in Product Design learning with AM.

Paper outline

In the following section, titled Developments and Product Design, we provide an overview of the how emerging technology provides new points of interest that are relevant for Design. In addition, we lay out our position on how technology develops in a non-linear fashion through the real-world uses and influences of relevant actors.

The third section focuses in on the emerging learning patterns of design education, which is historically influenced by the modernist Bauhaus tradition. However, the increased attention towards scientific methodologies and digital technologies following up to the millennium, calls for renewed learning frameworks for the education of designers. We link this to the development of new learning concepts for digital fabrication, increasingly found in elementary schools, fablabs, libraries and universities.

The fourth section focuses on our own pedagogical approaches to Additive Manufacturing. We provide two case studies from AHO from 2015 and 2016, one situated within the existing studio-learning framework, the other from within a lab environment.

The fifth section is dedicated to insights from the various teaching activities related to Additive Manufacturing. We then provide several points of discussion that are offered with respect to the modelling of an 'Additive Experiential Learning Cycle'.

In the conclusion we suggest several key matters that may arise for design-based pedagogies within and beyond Product Design for making and critiquing within learning about digital fabrication.

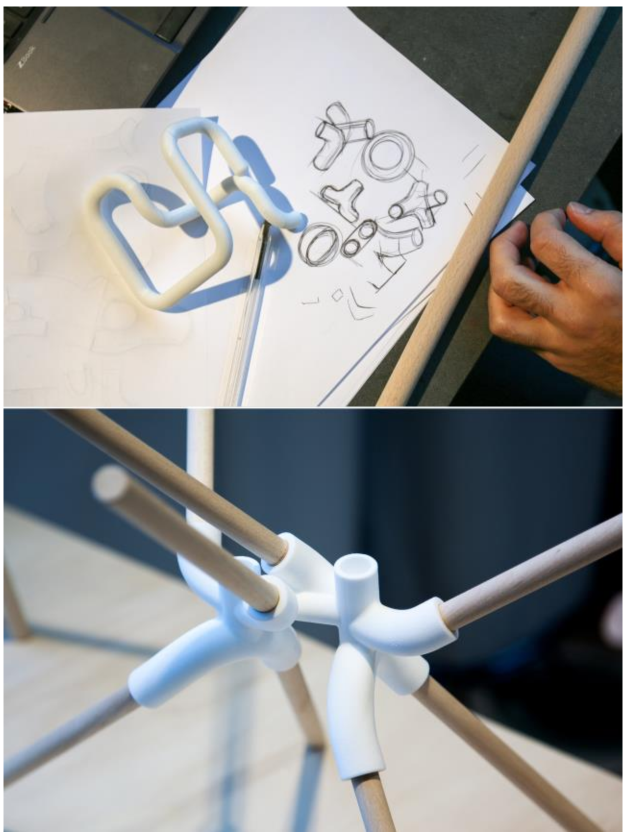

Figure 2 – RP and AM play overlapping roles in a product development strategy, such as in this expressive joinery, where the design can be 3incrementally improved based on the intended production technique, SLS. Design by Seyedamirarsalan Shamabadi. Photo by William Lavatelli Kempton

2. DEVELOPMENTS AND PRODUCT DESIGN: CHANGE AND TECHNOLOGY

In order to understand how 3D printing emerges as a potential enabler of new sites of learning, we first turn to a brief summary of the technology and its contemporary contexts of use and interpretation.

From Rapid Prototyping to Additive Manufacturing

At the turn of this century, users of Additive Manufacturing equipment, still labelled Rapid Prototyping, started to talk about using the technology for manufacturing end-user products. After the success of several commercial projects, such as customizable hearing aids [12], research efforts were intensified. Before 2001, a hearing aid was best suited to need on the basis of a limited range of shapes. Peoples' inner ears are very individual and some people did not find a hearing aid that fitted them well. Two companies, Siemens and Phonak, developed a system were the doctor took a quick silicon cast of a patient's ear. This was then sent to be scanned, after which room for the electronics was allocated in the digital file and then printed, for instance using SLA or DLP. Electronics were then mounted and the hearing aided shipped back to the doctor and patient. The success criteria here lay within three parameters that should be present: 1) There should be a complex shaped product, 2) It should be a high cost product, and 3) It should be a small product.

The success of the hearing aid example influenced the relatively small Rapid Prototyping (RP) industry to apply this view for developing products, now labelled as Additive Manufacturing (AM). This gave way to Rapid Manufacturing [13], which in 2009 was formalized as Additive Manufacturing. At this stage, AM was seen as a manufacturing process for the production of end-use artefacts. Several calls have since been made for developing new ways of designing for AM [14].

Our ongoing research initiatives have been motivated by this call and we relate them to developing appropriate design centred pedagogies. As Additive Manufacturing is connected to emerging technologies, we next provide a theoretical positioning on our view of AM and its non-linear development by its relevant social actors, in particular those in design.

Design, change and technology

In order to further an argument concerning the use of emerging technologies in a design education setting, we first provide an analytical framework for understanding how design relates to change and technology. This is relevant because Product Design, in moving from craft to industrial design, has actively engaged with technology [15].

On an instrumental level, design practice engages with technology as a means to analyse, ideate, communicate and mediate design ideas and concepts [16]. The creation of physical prototypes (Figure 2) in a multitude of materials remains common practice among product design students. This is often complemented by digital renderings, visualisations and animations for conveying elements of a design proposal.

On a materialistic level, design practice plays a role in developing technical processes and capabilities into new forms of radical or incremental innovation [17]. Through their knowledge of user behaviour, material production, cultural or even environmental factors, designers create artefact concepts or proposals. Whether they be material or immaterial, such as the design of new services, the nature of these propositions may span from readily consumable products or simply as critical makings and design explorations of 'what might be', either as utopian or dystopian visions [18].

Change and un/determinism

The argument as to whether technology influences, or is influenced by societal factors, can be reduced to discussions of optimisation, rationality and linearity in technological development. While contemporary accounts point to the fact that linear, deterministic opinions are commonplace [19], design-oriented research on technology and change point emphasise a uni-linear, non-deterministic view on technology and development.

Although the concept of technological determinism may take on several forms, it typically presents of technology as following a linear and logical path, as if it has a “life of its own” [20]. In such a view, technological components forever strive to optimise and improve according to the ‘laws of technology’. Social forces then proceed in accordance with these technological changes.

Our overlaying argument for technological change is an emphasis of social actors playing a decisive role in developing how technological innovation occurs. This is deeply founded in constructivist and critical technology frameworks located in Science Technology Studies (STS) [21], [22]. From these frames, technological innovation is seen as a non-linear force, directed by the various users and cultures that engage with it productively. Examples of social constructions contributing to technological change are found in Bijker’s analysis of the social of the bicycle at the turn of the 20th century [23]. At the time, cycling was seen as a risky “gentleman’s sport”, due to the inherent danger of the large wheeled, velocipede bicycle. While other, smaller wheeled designs were available, they were seen are more utilitarian. Only after Dunlop’s re-invention of the pneumatic rubber tire, did the identically sized wheels of the Safety bike gain recognition as the archetypal bicycle design. Concerning developments in digital technologies in the past three decades in particular, STS scholars have argued for more nuanced, material understandings of the role of technology in social life [24].

Views on design and emerging technology

Since the commercialisation of the Internet and the attendant rise of consumer level computing and more recently mobile devices and communication, emerging digital technologies have sparked wide interest in popular discourse as to new applications and improvement of contemporary circumstances. Most recently, this has been the case concerning artificial intelligence, machine learning, and the robotisation of labour [25]. In a design view, these technological developments and their surrounding discourse of progress, change and even fear, may also be seen a source of critique and speculation.

It is within Design Studies that these views are taken up, where STS tends to not inform its technology critiques through the articulation of practices and practice based knowledge by designer-researchers [26]. Methodologies for a reflexive, critical yet constructive approach to emerging technologies, such as those appearing in Speculative Design and experimental design writing critiquing prevalent views on AM [27], suggest ways that addressing commonly held presumptions and fallacies may “shift the discussion on technology beyond the fields of experts to a broad popular audience” [28]. This way, design can also inform a view of technological futures by alternative means, be it utopic or dystopic.

Additive Manufacturing is still arguably an emerging technology, and taken up with interest in different fields and among diverse actors. By unpacking the different claims that are being made for Additive Manufacturing, we may further an understand what role it may play for design. In tandem, we may ask and explore how a design centred view may inform pedagogies of productive engagement and future literacies.

Technological non-deterministic view of AM

Following a view of technology as being shaped and appropriated by its relevant social contexts, we argue that emerging technological developments do not follow a fixed track of continuous refinement. [21], [22]. Rather, a web of complex social forces, from non-users to early adopters, can be understood as constantly realigning a contemporary understanding of a certain technology.

Building on this framework of technological non-determinism, Kempton outlines a view of the socio-technical development of 3D printing and Additive Manufacturing as constructed between a set of relevant social groups. This includes the 3D printer inventor, business, design, and layperson ‘maker’[9], who view the digital fabrication technology according to different technological frames. While some see 3D printing as a potential for new, localised distribution paradigms, by others it is interpreted as a platform for creative inquiry.

3D printing can be understood as sparking visions into futuring activities and political imaginaries, such as the decentralisation of production, the rise of maker-turned-entrepreneurial businesses, and commons-based utopias [29]. As it does this, the technology in context brings design into popular circulation, where making and material production skills become necessary and may be understood more accessible via acts of designing.

In order to unpack the role of digital fabrication within design pedagogy, we next turn to the pedagogical and experiential spaces where design learning occurs.

3. LEARNING CHALLENGES AND PRODUCT DESIGN: PHYSICAL - DIGITAL - PHYSICAL

From Bauhaus to fablab - Evolving design cultures

The educative frameworks around design pedagogy are largely influenced by the opposing cultures of the ‘hard’ technology cultures, and the ‘soft’ cultures surrounding arts, humanism and democracy [6]. Attempts by design institutions to uniting these opposing cultures during the last century have largely influenced ways in which design pedagogy is conceptualised and effected. One such attempt is found in the Bauhaus movement of the 1920s, which sought to develop a vision for modern design based on rationality and Gestalt theory. However, its cherishing of rationalized and industrialised form can itself be understood as aligning to the ‘hard’ culture of science and technology. This is conveyed through an obsession with geometric form and abundance of cement, steel and glass material use.

Pedagogical models through which designers are educated have gone through considerable changes the previous century yet they have not always been well articulated in terms of learning theory and elaborated case based analysis as in other domains of teaching and learning. While craftsmanship and theory were separated in the design and architecture education, the Bauhaus movement emphasized the re-integration of aesthetics, craft and technology [2]. This was in part achieved through combining the master-student apprenticeship model together with theoretical subjects. The studio-based environment, whereby students combine hands-on experiences with theory, remains a dominant pedagogical model for the education of designers [30], strongly influenced by the Bauhaus model.

Digital Bauhaus

Ehn's manifesto for the 'digital Bauhaus' [6] called for a bridging of the softer values of digital materiality with the rationality of the initial Bauhaus movement. The reason for this bridging, he claimed, is to make way for a 'third culture', inspired by a new generation of hackers, nerds and digerati who critically and creatively unite 'modern information and communication technology with design, art, culture and society'. [6, p. 210].

This manifesto appears at the turn of the 21st century when Human-computer interaction (HCI) and interaction design became more prominent in the education of design pedagogy.

The Bauhaus educational model of master and apprentice has since become more professionally inclusive, while still embracing a studio model. However, this studio model is under scrutiny, as new sites of design knowledge [31] are increasingly found in emerging places such as makerspaces, incubators and fabrication labs.

From studio to lab learning

As a complement to building theoretical knowledge, the laboratory setting points towards the building of practical expertise and reflection. Because of the emphasis of creating both theoretical as well as practical knowledge within design schools, the presence of such laboratories is relevant. The scope and objectives of these labs may be many, as they could refer to anything from electronics labs to also include tool shops.

Developments in computer technology and computational software has also led to the foundation of computational design labs across schools and universities. Other examples of laboratories include communal making labs, popularized through initiatives such as MIT's FabLab [32], which may increasingly be found in such diverse places as libraries, schools and old industrial facilities [33]. Inspired by a hobbyist attitude towards material engagement [34], these 'maker' labs in turn inspire research into new models of formal and informal learning processes. Such research can be found in the development of new learning programmes for elementary-level school, were making labs complement the established STEM (Science, Technology, Engineering, Maths) programs.

Early advocators of making labs in elementary-level schools [35] point to Papert's constructionist learning pedagogy which pioneered the use of Logo programming language for teaching maths to young learners [36]. Similarly, making labs are envisioned as spaces for facilitating new literacies towards design and engineering [37].

As with arts-related teaching which emphasizes a representational mode of learning, the emerging maker-oriented teaching programs are often discussed in the elementary level schools. Programs such as Fab-Lab@school [38] and the Fablearn programme discuss various problematics such as assessment of designerly skills, its relation into existing STEM learning, to mention a few.

Design, learning and digital fabrication laboratories

The types of laboratories within a design and engineering context in higher education can be understood as being either developmental, research and educational [39]. In a practice setting, both the developmental and research laboratories act as places for generating new knowledge. The objective of the educational laboratory, however, is more closely related to providing students appropriate instruction to allow them to operate the necessary tools, procedures or methods of the lab.

Celani [2] argues that digital fabrication labs, located within art, design or engineering schools, do not necessarily have such clear distinctions. Her reasoning is that the relative expenses of running these labs necessitate that they are take on the three laboratory roles simultaneously – a digital fabrication lab might run a model building service for students, staff or even external businesses, while acting as an instructional lab for students.

Celani's discussion culminates in an elaboration of the pedagogical side of the digital fabrication lab from an architectural learning point of view. As she points out, the emerging role of the digital fabrication laboratory is to compliment techniques such as parametric modelling, CAD scripting, algorithmic design etc. Such a shift, in her view, allows architecture students to get closer to novel production processes that such as what Oxman calls a "cultural shift" from contemporary architecture practices and discourses [40].

From our design point of view, we also see the role of the digital fabrication laboratory as coinciding with other techniques, placing the emphasis on both digital and practical literacies. However, our pedagogical argument for learning about Additive Manufacturing and its application in Product Design also moves beyond the mere employment of techniques. It seeks to understand them in relation to new societal consequences and impacts. In the following section, we refer to a Critical Making framework to address these issues. This is a framework for sociotechnical inquiry that blends both theoretical and pragmatic engagements. A key aspect of the framework lies in integrating both critical analysis with physical 'making' practices.

Figure 3 – A speculative student design concept which envisions how bugs and ants may be a part of the everyday lunchbox. Design by Zane Cerpina. Photo by William Lavatelli Kempton.

From prototyping to critical making

Prototyping remains a common practice among designers and student designers (Figure 3). It allows them to constantly create and reiterate on initial design ideas, guiding them towards their envisioned objectives. A crucial role of digital fabrication in design education is to allow students to create mock-ups, prototypes and representations of their work. Although the rationale for making models may vary depending on the individual project, a common trait of a prototype is to act as a "a vessel for traversing a design space", or as "purposefully formed manifestations of ideas" [41]. In such a view, the making of prototypes can be seen as a filter between design ideas and concrete outcomes.

While AM facilitates the making of complex digital models into physical prototypes [42], its role for engaging physical and digital material hybrids is also emphasized in scholarly work. Concepts such as Critical Making, initially coined by Matt Ratto [24], emphasizes critique and material exploration in order to engage with theoretical concepts that go beyond the technical capabilities of 3D printing. In relation to AM, Critical Making can be used to understand connected concepts such as legislation (ramifications and potentials of "open-source" design sharing), citizen involvement, and new literacies (new skills in a digital economy) [43]. Ratto's version of Critical Making uses AM to facilitate a discussion and critique of emerging technologies and social concepts, emphasising "the shared acts of making rather than the evocative object" itself [24, p. 253]. However, others such as Hertz position Critical Making closer to exploratory material-making practices [44]. They may be taken up as a point of departure for "encouraging the builders of technology—whether hackers, engineers, industrial designers, or technology-oriented artists—to step back and re-evaluate the assumptions and values being embedded into their technological designs" [45].

Our pedagogical view on Critical Making, as Ratto points to, focuses on the procedural and developmental learning activities of making, rather than their artefactual outcomes (as may be seen in a rather traditional or formalist view of Product Design). However, we are also aligned to Hertz' view of critical engagement with technology, in this case digital fabrication, as a necessary re-evaluation process. In order to achieve this, we see the need for producing artefacts that can help to articulate and initiate new discussions. Critical Making activities therefore form part of a framework of devising an experiential pedagogy for AM product design. In the next section we suggest ways in which this may be achieved.

Combining these efforts for an experiential learning model

The emerging role of AM, from its use in making prototypes to critical making engagements, has significance in the development of our learning model for digital fabrication in design. While the role of AM for creating prototypes and design representations remains important for design learning, this role meets only part of the challenge. Other social factors, such as citizen involvement, legislation and digital literacies, are all relevant challenges to understanding AM. A Critical Making methodology might help reveal aspects of these challenges but seldom in AM literatures, academic and popular, do we see this taken up in terms of pedagogies, digital literacies and above all design located knowledge building and sharing.

In the next section we examine how these perspectives might help us further elaborate a learning model for AM in which our wider sociocultural and developmental view on learning may be framed with reference to experiential learning. While we draw on such a model from the learning sciences, our own view and resulting model are informed by design based pedagogies and modes of making and reflecting.

4. ADDITIVE MANUFACTURING AND EXPERIENTIAL LEARNING, A MODEL

Extending on the critical and developmental processes related to design and Additive Manufacturing, we will now turn towards a reflection on pedagogical models for teaching and learning AM within Product Design education. In this section we explain the principal directions in which AM is being taught and facilitated within the context of design education at AHO. We then present two views for pedagogy and AM, one with a focus on concepts for learning with technology and another to learning 'through' technology. Together these views inform an experiential learning model for design and Additive Manufacturing.

Digital fabrication at AHO

Digital fabrication at AHO is primarily performed around the lab environment where most tools are located. While laser cutting and CNC milling is integrated into the woodworking lab, 3D printing is located within a lab with restricted access, owning to the fact that 3D printing techniques have traditionally centred on plastic powder-based processes. More recent tools however, have come to include liquid-based and solid-based desktop fabrication, such as with Ultimaker and Formlabs 3D printers. Portable fabrication tools also influence the way in which students interact with digital fabrication, altering their threshold for when to make physical replications of their digital models [46]. What this brings near is the need to understand the emerging roles of digital fabrication within pedagogical settings.

How can design pedagogy be facilitated through a closed lab environment, and how can students challenge the role of AM through their use of digital fabrication?

Learning with and through technology

Drawing on sociotechnical frameworks of technology [47] we have built understanding of how Product Design practices may be positioned in the emerging development of AM technology. As mentioned, this perspective provides a foundational underpinning to our pedagogy on design and technology, as it leans design activity away from technical activities, to an emphasis of design in a sociocultural setting. However, within our pedagogical framework these two views complement each other in learning how to relate to AM in Product Design.

The teaching model at AHO on both bachelors and masters level is principally studio-based. Following the Bauhaus model of project development through project-based learning,, students conceptualise, develop and define their projects throughout the semester, by way of consultation with tutors and between themselves in peer based learning in which co-creation features. A prospectively oriented Product Design student might formulate their project in collaboration with a specific client, through set of technologies, based on a "wicked problem" or through open-ended play. Through workshops, lectures and project reviews, design students are confronted with a wide variety of methods [48] that may help them structure their design processes.

While digital fabrication, in particular through the use of 3D printers, has been incorporated throughout the five-year industrial design programme, its focus has primarily been on the prototyping capabilities of AM. In relation to conventional studio-based teaching, digital fabrication is often applied in relation to processes and methods focusing on physical prototyping. While model-making and prototyping might occur during the project timeline, digital fabrication is often at latter stages of students' projects, as consumption of time, cost of making models, the need for accurate CAD models play in. As digital fabrication tools, such as desktop-based printers are getting more accessible, however, patterns of use also change. Students are encouraged to examine their own processes of learning and to track and document its iterative, developmental and production based inquiries.

An approach to learning and digital fabrication

We now turn to new approaches to learning and digital fabrication that contrast with the conventional "prototyping" frameworks of digital fabrication.

Since 2015, a practice-oriented course that teaches digital fabrication has been taught at the Oslo School of Architecture and Design. As with Gershenfeld's [32] motivation for creating an experimental laboratory environment in which students could acquire a new set of literacies to critically engage with digital fabrication, the course focuses on open-ended exploration.

Labelled "Digital fabrication technologies and processes", the course compliments the traditional studio-environment by providing explicit focus on the technological components, materials and tools of digital fabrication. Technical literacy is built via active engagement with the tools through a series of rapid design explorations. The course culminates in a 5-day project where the newfound knowledge is demonstrated through an exhibition.

The space presents outcomes that are explained and oriented in terms of their processes of making and use potential. The exhibition offers other students outside of Product Design access to the course and its pedagogies as does the gallery setting at AHO that is open to a wider public and more generally connected to other exhibitions that travel out from the institution's design spaces and exhibition arena to other related ones.

Building experiential learning

The overall structure of the course is set up around a pedagogical frame which focuses on active experimentation and reflection on the materials and processes that make up digital fabrication. This bears some resemblance to Kolb's experiential learning cycle [49]. Kolb's model, which springs out of Dewey's pragmatist philosophy of learning, emphasises a "link to real world objects, not bound by the organisation of subject-matter" [50]. This pedagogical model is structured around four modes experience that involve *Concrete Experience*, *Reflective Observation*, *Abstract Conceptualization* and *Active Experimentation*.

We apply such a model of learning in the digital fabrication course. The course took place in both 2015 and 2016, involved between 13 and 19 students, and 3 design teachers. The course ran over a 11 week long semester.

The students on the course have a varying degree of proficiency and prior knowledge in using the fabrication tools, are given access to specific processes after a brief introduction (*Concrete Experience*). The "3D printer shop", which acts as the classroom, is packed with a diverse set of AM and 3D printing processes that work with a diverse set of materials. Some of the tools that the students interact with are desktop-sized Ultimaker 3D printers that extrude filaments of plastic material, large SLS printers that sinter layers of nylon powders, laser-cutting in wood and acrylic, experimental 3D printers that extrude and fabricate with clay materials, and Stereolithography (SLA) printers that use liquid photopolymers to build prototypes.

Figure 4 – Artefacts, tools and materials in the process of designing. Designs by Hans-Martin Erlandsen. Photo by William Lavatelli Kempton.

After an introduction of how to use the different manufacturing devices, students were challenged with individual assignments, which are shared with the rest of the group through weekly presentations. This way the students were encouraged to reflect on their experiences (*Reflective Observation)*. The resulting material experiments then formed a material library which acts as an input and abstraction for later experimentation (*Abstract Conceptualisation)*. Figures 3, 4 and 5 show a set of material experimentations that are a result of iterative cycles of experimentation. Figure 4 displays artefacts from the iterative design process of a veneered computer mouse. Here the student is challenged by the idea of using the 3D printer as a tool *for manufacturing* [17] traditional materials such as wooden veneer. In the process, several types of AM equipment for moulding the veneer were created, in addition to the main body of the mouse.

Figure 5 illustrates how a 3D printer is programmed to weave layers of clay material (*Active Experimentation)*. Whereas 3D printers are traditionally employed to imitate the shape of a digitally created form, this product design student went about forcing the 3D printer into weaving layers of material into each other, much like the weaving of fabric.

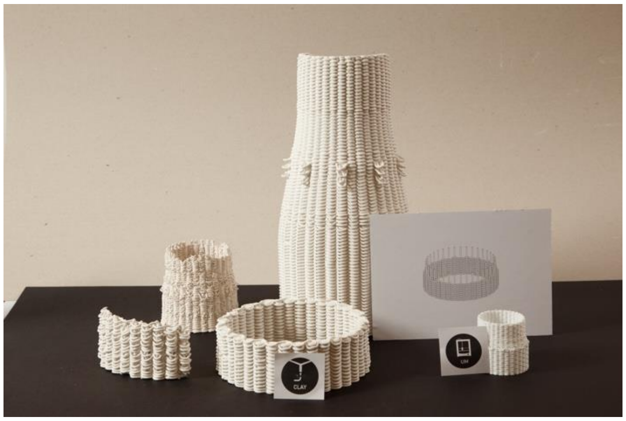

Figure 5 – Models and prototypes of an attempt to weave clay using a desktop-sized 3D printer. Design by Jon Bjørn Dundas Morå. Photo by William Lavatelli Kempton.

At the end of the semester, students were involved in a week-long workshop, which is presented as an exhibition open to both students and visitors. The theme of the exhibition was determined by the assignments and explorations carried out throughout the semester. Figure 6 shows an excerpt from curation of the exhibition "Physical is the new Digital". Through practice-based inquiry, the students on the course sought to develop new material understandings, themed around sound, light, typography and traditional craft practices.

Figure 6 – From the exhibition "Physical Is The New Digital". Photo by William Lavatelli Kempton.

Towards an Additive Experiential Learning Model

In contrast to a view on design that seeks to understand problems and translate them into solutions, the course enacts an open-ended approach, requiring the students themselves to consider the many potentialities and convergences of digital fabrication. If we reconsider Kolb's experiential cycle of learning in the context digital fabrication, it is possible, when one understands how iterative learning transpires, to move in and out of aspects of the cycle in non-linear ways.

We call this dynamic and iteratively non-linear approach an *Additive Experiential Learning Model*. It is one that is invested with production-based knowledge about possibilities and potential that are informed by the malleable and flexible character of digital fabrication.

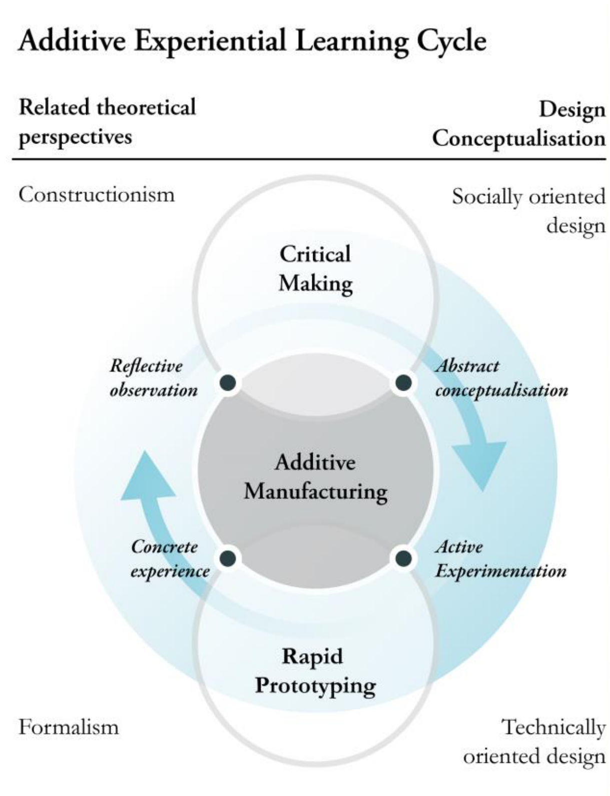

Figure 7 – 'The Additive Experiential Learning Cycle'. This presents a non-linear approach to design and digital fabrication. Learning passes through various framings of material engagement, such as Rapid Prototyping and Critical Making.

At the centre of our Additive Experiential Learning Model (Figure 7), we place Additive Manufacturing as it overlaps between technical and socially oriented conceptualisations of design. We assign the concept of Rapid Prototyping and Critical making to these conceptualisations.

The model can be read as cycling in and out AM, as it emphasises various modes of design conceptualisation. As Rapid Prototyping emphasises the utility of digital fabrication towards model making, it links to a mode of design which is technically oriented. This is necessary in order to generate hands-on engagement with fabrication techniques and tools. On the other hand, we link reflective and analytical actions to the concept of Critical Making, as a way of contextualising the artefactual outcomes of RP.

5. LEARNING ADDITIVE MANUFACTURING, INSIGHTS FOR DESIGN EDUCATION

In teaching, observing and assessing the course, including inputs from students during the course and from their course evaluations, we have arrived at a number of learning insights on teaching AM to design students. These insights need to be seen as connected, despite their specifics, if we are to best conceptualise and further practice an experientially rich and pedagogically dynamic approach to learning with and through AM in Product Design. The insights refer to the paradox of how much freedom to allow in designing with AM, moving beyond notions of the awesome idea of a product, and the issue of designing for future unknowns.

Too much design freedom – A recurring debate when working with AM is the vast amount of form freedom that comes with its technique. As there is no need to create predefined tools or moulds, AM is largely able to produce unique, artefacts with seemingly endless points of variation. Although this proves to be a fallacy (such as the relatively limited material freedom of AM or that fact that clay printing is largely restricted in terms of material overhang), students are often challenged by the seemingly endless form freedom that come with AM. While this in itself can be a source of inspiration, students often struggle to limit themselves to a particular aspect or conceptual idea. We suggest that AM pedagogical frameworks emphasise this topic.

Beyond the awesome product idea – design students, in particular those specialising on industrial design, are often inclined to create novel product solutions to everyday annoyances, such as cable clutter, or an abundance of keys in their pockets. While this may be a relevant design task, it does not necessarily correspond with their initial learning objectives for AM. We suggest students consider their product ideas and concepts as vessels for new novel material investigation or interaction, more than as a manufacturing platform to their ideas.

Designing for future unknowns – As digital fabrication is often entwined in both utopian and dystopian design speculation, design students are often tempted to conceptualise AM for radical future products and artefacts. This however, may become problematic if emphasis is solely put on a conceptualisation of an AM technique. Aligned with our argument for an emphasis of the relevant social groups that interact with AM, we suggest that such radical design concepts may benefit from being tuned to the interests of relevant groups. For instance, if conceptualising how AM might influence medical surgery, it is important to consider stakeholders and actors involved.

6. DISCUSSION AND CONCLUSION

In this paper we have attempted to address a series of learning challenges related to building design based pedagogies between Product Design and Additive Manufacturing.

Firstly, if AM is to play a different role within design, focus must be shifted from technique to a broader contextualisation of emerging technology in societal contexts. Secondly, how can this be related to product design teaching on AM. Thirdly, what are the ways in which design students can learn and share their newfound knowledge on AM which seeks to contextualise technique within a socially oriented view of design.

Through these learning challenges we stated a series of research questions which relate to – a) What are the emerging discourses connected to Additive Manufacturing? b) How can we elaborate on pedagogical models which allow prospective designers to understand and engage with digital fabrication?

In order to address our view on change and technology, we presented a framework for discussing AM as an emerging technology. This comes out of constructivist and STS frameworks which emphasise a non-deterministic view of technology. We take on this view to further our argument for the active role design has in the development of technology.

Further, we addressed learning challenges related to design and digital fabrication, pointing to past and present modes of pedagogy concerning product design, digital fabrication, Rapid Prototyping and Additive Manufacturing. While most design pedagogy adheres to the studio-based models derived from Bauhaus foundations, increasingly amount of design learning is happening in the contexts of digital fabrication labs. While these labs have traditionally been emphasised as model-making facilities serving the studio environment, their role is becoming more prominent as independent sites of experiential learning that is marked by an emerging design centred culture of making and shaping, DIY and hacking. Notions such as maker spaces and fablabs, found both in and out of university campuses, have come to represent a mode of learning which involves practice-based inquiry and open-ended exploration with digital and analogue ‘making’ technologies, from programming with Arduino boards, to laser cutting, CNC milling and 3D printing.

In the latter sections of this article we went to specific learning contexts for design and AM, though our own approaches to teaching at The Oslo School of Architecture and Design. Our overall pedagogical frameworks consist of two complimentary views to AM teaching. One view emphasizes design learning ‘with’ technology, the other focuses on learning ‘through’ technology. While the former can be seen as forwarding a view digital fabrication for purposes of making visual representations, models, mock-ups and prototypes, the latter prioritises a critical making perspective.

Taken together, in a mode of learning by doing, returning to Dewey’s pragmatist perspective, these two views – learning through and learning with technology – build towards an experiential learning model for design and Additive Manufacturing. We position this model within Kolb’s schema of experiential learning. In doing so, we focus on the emergent, developmental, and contextual in situating Product Design and digital fabrication within what we label an “Additive Experiential Learning Cycle”.

In our model of the “Additive Experiential Learning Cycle”, the learning cycle is a non-linear approach to design and digital fabrication. It passes through different frameworks of material engagement, from technically oriented concepts such as Rapid Prototyping, through to socially oriented concepts such as Critical Making. We argue that such views complement each other when building experiential knowledge on Additive Manufacturing. They offer developmental and situated perspectives on learning with technology, both in a pragmatics of ‘mediation’ and through practices of critical making. These perspectives drawn from Product Design may be useful for other design-based approaches to learning with and through technologies in the wider contexts of digital fabrication.

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