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.

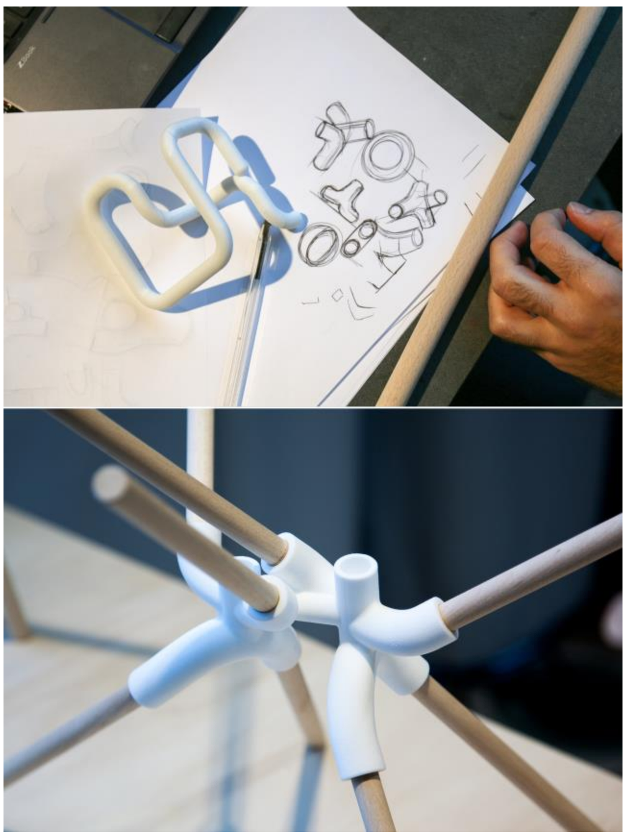

Figure 2 – RP and AM play overlapping roles in a product development strategy, such as in this expressive joinery, where the design can be 3incrementally improved based on the intended production technique, SLS. Design by Seyedamirarsalan Shamabadi. Photo by William Lavatelli Kempton

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.

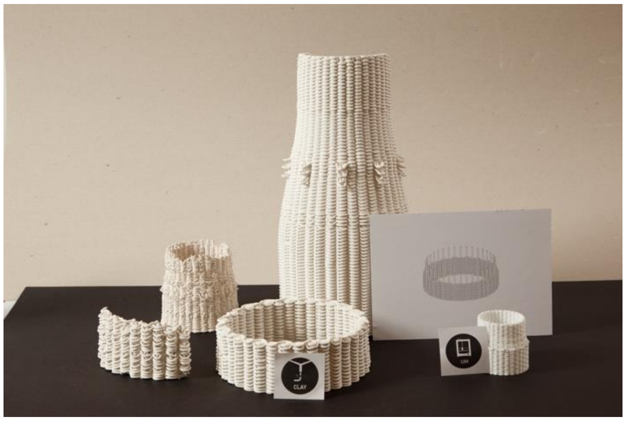

Figure 5 – Models and prototypes of an attempt to weave clay using a desktop-sized 3D printer. Design by Jon Bjørn Dundas Morå. Photo by William Lavatelli Kempton.

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.

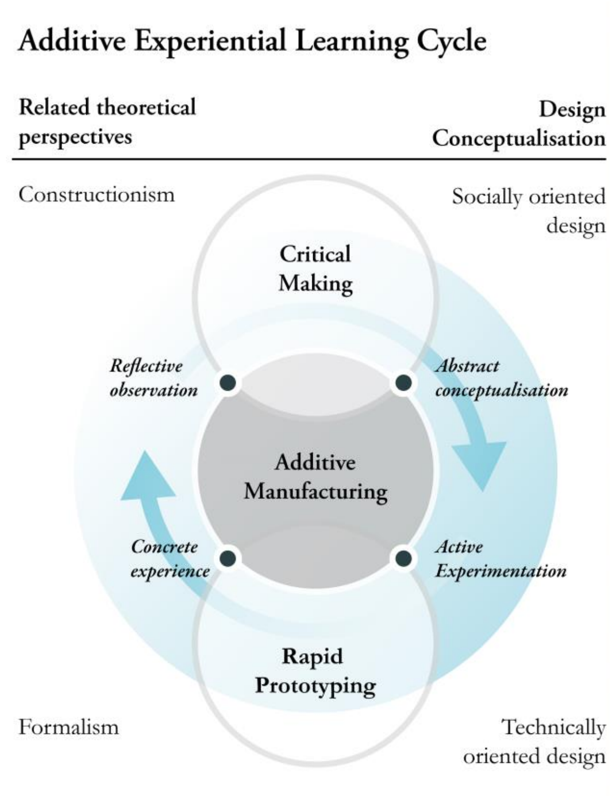

Figure 7 – 'The Additive Experiential Learning Cycle'. This presents a non-linear approach to design and digital fabrication. Learning passes through various framings of material engagement, such as Rapid Prototyping and Critical Making.

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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