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Educating designers with 3D printers: a postphenomenological perspective on maker and design pedagogy

Nenad Pavel, Oslo Metropolitan University, Norway

Abstract

Learning in makerspaces is free from curriculum and evaluation and is believed to yield practical, self-driven and solution-oriented learners. This study explores how makerspace pedagogy can be emulated in formal higher education settings to support this kind of learning. Action research was used to cultivate and review this pedagogical approach in three repeated design studio courses using three-dimensional (3D) printing lab. The maker pedagogy was to support self-driven learning emerging in relationship between learners, their social environment and technology media. Maker and design pedagogy has been further theoretically developed using postphenomenology as a process of learners' adoption of 3D printers in own design practice, learners' adaptation to the affordances of the 3D printers, and attainment of learners' own goals in social contexts using 3D printing technology. Finally, the study indicates how shifting from constructivist to postphenomenological theoretical concepts can give new insights and strengthen sustainable pedagogical practices. Limitations and opportunities for maker pedagogy in formal education are addressed with these new insights.

Keywords

Technological Media, Design Pedagogy, Maker Pedagogy, Postphenomenology, 3D print.

Introduction: emulating makerspace qualities in formal education

The emergence of alternative informal education, such as makerspaces, has drawn the attention of educators. Some formal study programs in the field of science, technology, engineering, and mathematics have seized the opportunity to borrow some makerspace learning qualities. As a result, makerspace workshops have been established at universities with the promise to encourage an experimental and hands-on approach to learning. The existing literature (Ford & Minshall 2019) has shown many of these attempts to integrate makerspace pedagogy to increase student engagement, motivation, curriculum implementation, and learning efficiency. Benefits have also been noted to include increased student creativity, especially the ability to 'define problems' and 'design solutions' as core engineering practices (Quinn & Bell 2013). Accordingly, this kind of thinking is important for learners' 'individual agency and can foster learners' autonomy' (45).

However, researchers such as Godhe, et.al., (2019) have scrutinized these claims due to the issues arising from attempts to emulate makerspace learning approaches in formal education. They question the promise of maker-based education and called for research on not only successful cases of the implementation of maker technology and pedagogy in formal education but also those producing average and failed results. Their paper addresses issues and proposes both the reconfiguration of maker technologies and calls for new ideas for 'alternative conceptual pedagogical frameworks that move beyond the narrow concerns of maker education' (11) that can fit formal education in a more effective way. Of the issues raised in this paper, I would like to outline and elaborate on two.

The first issue involves curricula or learning content. Maker movements rest on the free endeavors of their participants, who learn through play in a social setting and freely explore what interests them (Martin 2015). Therefore, learning through maker technologies, according to some theoreticians (Martin 2015; Bevan 2017), should facilitate learners' agency by freeing them from curriculum and instruction. Furthermore, it should be process-oriented and participatory, with unpredictable outcomes, and should transfer the learning responsibility to learners. If this is to happen outside the makerspace setting and be transferred to the formal educational setting, the challenge becomes planning the curriculum. Thus, we must ask how learners choose what to learn. This question is important, as future learners must scrutinize, systematize, and make sense of the saturated information they encounter daily.

The second challenge is instructional. The makerspace pedagogical model poses the concept of constructionism, which implies learning by making, failing, and experimenting versus instructionism, which implies successful outcomes and avoidance of errors (Bevan 2017). If learning is not content-led but process-led, how should pedagogical instructions be formulated to ensure self-reliance in a formal learning setting? This is an important question because academic institutions are provided with the societal task of ensuring that learning outcomes are achieved to a satisfactory level (EURspace, 2019). At the same time, informal learning approaches and learning at work are gaining interest as a way for learners to adjust to the continually changing job markets by demonstrating their own agency and lifelong learning.

In addition to the challenges with content and instruction, inclusion is also a concern when cultivating maker pedagogy in formal education. Specifically, formal education must provide a learning experience for everyone, not just for those students who have a special interest in making or an accessibility to maker tools and communities. Furthermore, it must comply with a certain administrative, temporal framework with defined learning outcomes.

Maker pedagogy in the design studio in formal education

There are organizational and pedagogical practices that stand in the way of emulating makerspace pedagogy in formal education, but there are also limits in the theoretical approaches to implementing these emulations, which I will address in this section.

Literature reviews on the topic of maker technologies and learning (Vossoughi & Bevan 2014; Ford & Minshall 2019) have shown that pedagogues and researchers are discussing learner-centered theories, particularly constructivist and constructionist approaches regarding learning with maker technologies at all levels of education. In contrast, in studies on learning at work, network-based organizational theories are more present. In educational research, constructivism is especially visible in the recurring concepts of problem-based learning, followed by other constructivist concepts such as authentic, inquiry-based, and experiential learning (Pavel 2021). Constructivism assumes that learners generate their own construct of knowledge through experiences rather than by following instructions. Another theoretical construct often linked to learning by making is Papert's constructionism (Vossoughi & Bevan 2014), in which construction happens when the knowledge is put to practical use by learners. Maker pedagogy is also related to process-based learning inspired by design thinking such as pedagogical principles of hack, adapt, design and create (Bullock & Sator, 2016). The other approach to understand maker pedagogy relies on describing attitudes such as: (a) seeking know-ledge, (b) exploring opportunities, (c) assuming responsibility, and (d) embracing change; as well as types of competencies: creative thinking, collaboration, and communication Nadelson and Seifert (2016)

To study maker approaches to learning in formal education, the pedagogical setting of the design studio provides a useful research site for many reasons. It supports experimentation, failure, defining problems and designing solutions as part of the design process. The design studio is situational, includes maker technology media, and can be characterized by peer learning. In this way, the design studio can be seen as a formal education counterpart of informal makerspace pedagogy. The similarities continue when theoretical approaches are compared.

The design studio in literature has also been extensively linked to constructivism (Sawyer 2017), where learning is characterized by cycles of critical reflection, as described by Schön (2015). However, differences can be found, especially in the way expected learning and material outcomes are defined by curricula, codes of professional practice, and the pedagogue, who is visibly present in a design studio. Contrary to design pedagogy, makerspace approach is fully dependent on interests of the makerspace participants. Martin (2015) explains how learners in makerspace choose to make what is ‘fun’ and ‘cool’ for the maker group.

Regarding organizational practices, it is necessary to acknowledge that makerspace pedagogy is emerging in a specific sociotechnological setting. This setting is characterized by voluntary learning groups, three-dimensional (3D) printers, cheap sensors, and mini-personal computer components, such as Arduino. The challenge with these theories is that both constructivism and constructionism as well as process led learning theories put the learner at the center and neglect the effects of this rapidly changing sociotechnological environment.

Research design: action research, direct content analysis and postphenomenology

This study focuses on practical application of maker pedagogy in a 3D printing course repeated over three years in formal design higher education. With each repetition, the course has been modified to facilitate maker pedagogy. Modifications were supported by analysis of a previous course and theoretical reflections. In this way action research methodology has been informed by pedagogical theory and evolving direct content analysis.

Teaching design studio in cycles of action research

Action research is an effective methodology for enacting and studying changes caused by technological mediation in real-life research settings, such as a design studio (Swann, 2002). Thus, it was chosen for this research, which had the main goal of cultivating learning and teaching practices in terms of creating new pedagogical approaches, relating these practices to relevant literature and theory, and elevating practitioners’ professional accountability (McNiff 2014). Action research is a way for teachers to reflect on and improve their practice, and in this study, inciting maker pedagogy in the design studio gives action research an emancipatory quality. The methodology of action research is described as narrative writing in the first person, in which cycles of action and reflection inform each other, leading to transformation (McNiff 2014).

In this study, three cycles of action research were implemented through three repeated and modified six-week introductory courses, with a different group of 45 first-year students for each cycle. The course was set up to on the basic premises of design (Simon) such as defining user needs, translating them into product specifications, and constructing and forming artefacts to answer these needs. Students worked in groups in which they were required to frame problems, design solutions, and manage workloads on their own as explained in the results section, where one exemplary project is described (see Figure 4). As the participants were just entering their studies, very few were familiar with 3D-printing technology. The course was situated in a bachelor's program in product design in one of the three design schools at the university level in 'COUNTRY'. The study program has its roots in arts and crafts, with a tradition of workshop skills, conceptual design ideation, and materiality of design. This setting, therefore, incorporates the challenges of maker pedagogy in formal education, which is additionally burdened by temporal and administrative demands, as well as a diverse group of learners in terms of their familiarity with maker and design processes. Furthermore, a new 3D print lab had recently opened, and the department's management was motivated to put 3D printers into pedagogical practice with novice students. The first course was introduced at the end of the first year of the product design study in 2017, followed by the second and third in 2018. The study was authorized by the Norwegian Council for Research Data as research in one's own practice and according to its ethical standards. These standards include participant consent, anonymization, and secure data handling.

I engaged two experienced and qualified colleagues to be critical friends which is common in action research methodology (Wennergren, 2016). One was present during daily activities, and the other provided feedback on learning outcomes. Together they assessed grades for students. They were engaged in assessing and providing critical discussion on the changing course description and task description for the students. They also collected data when multiple student groups participated in activities at the same time. The head of studies at the department was involved and provided opinions on behalf of the department. This arrangement allowed me to observe the research setting as a pedagogical situation and avoid grading projects myself, which would be unethical. Action research allows for the collection of real-life data as well as first-person involvement. This means that the data include records of designing in action, where students, in teams, discuss both the development and purpose of their prototypes without the involvement of teachers and conduct interviews through which they reflect on the designing experience. First-person involvement means that the researcher is not a mere observer but takes part, taking concrete action to improve their own pedagogical practice.

The cycles of action research were supported by direct content analysis. This approach applies theory to determine classification topics in advance (Hsieh & Shannon 2005). The method allows for the exploration of existing theoretical concepts within the data material. In this study, the actionable phase involved the implementation and observation of the design course. Direct content analysis was used in the reflection phase to probe different theoretical approaches through classifications and to develop explanations for what was happening in the design studio to inform modifications to the design studio course.

The data material therefore includes course descriptions and pedagogical instructions developed by teachers as an action plan for the next cycle or a revision of a previous cycle. Evidence from the course activities was used to analyze and evaluate the practical pedagogical outcomes of these pedagogical instructions. Participant observation of prototype presentations was recorded, and notes were taken. Archival data material includes reflection notes about the course by students and design reports in which students were instructed to describe and reflect on their design activities. Artefacts themselves were useful material, as they represented how technological mediation influenced the design outcomes. This evidence from the course activities was used in this study to qualitatively assess students' abilities to translate pedagogical instruction into learning activities and realize their own agency. The citations used in the descriptions of the findings section are representative citations from the classification categories in the revision cycles of these data. The data were compiled and processed in NVivo software in the NATIONAL language, and the citations and conclusions were translated for the purposes of this article.

This new theoretical and pedagogical framework evolved in the process of recoding data in three cycles of field and literature research. Throughout the process, many of the theoretical classifications were either not relevant to the data material or did not provide explanations that could give new insights for the studio-based maker pedagogy, leaving the postphenomenological explanation as prevalent. The classifications are described in detail in coming section 2.3.

Postphenomenological perspective: technologically mediated learning

The sets of classifications emerging from the postphenomenological analysis of the data gave different explanations to the learner centered approaches. The postphenomenological framework sets the relationship between learners and the technological environment in which learning happens as the focus of pedagogical effort. Merleau-Ponty (1996) explained that meaningful, embodied learning means that human bodily capacities, such as the mental, emotional, and physical, in relation to environmental affordances and constraints are the preconditions for learning. Learning means changing and transforming oneself in relation to the environment. Consequently, postphenomenology does not address learning, at least not as a psychological process. Rather, it addresses the phenomenon of mediation between humans and machines. This technologically arbitrated phenomenology (Ihde 2003) implies that not only are technologies used by humans but that this interaction is reciprocal. Namely, technologies transform human perceptions by amplifying or reducing certain aspects of the experience, and they translate human actions by inviting or prohibiting humans to do certain things (Rosenberger & Verbeek 2015). Thus, human learning can be seen as an outcome of human–technological mediations and these transformations. This is distinct from constructionism, which sees technology as being used by learners to construct and internalize knowledge. In this way postphenomenology allow for sociotechnological understanding of learning with 3D printing.

3D printing is a complex and versatile technology, as it is capable of fabricating 3D objects of nearly any shape or geometry through only one operational process. The mass-production character of the process is enabled as a digital model can be converted into material layers (Iancu, et.al, 2010). As a result, the link between physical and digital models becomes interchangeable, in that material and digital artefacts become representations of each other.

3D printers have not disrupted production, distribution, and consumption because they are not as effective when scaled up in production (Marak, et.al., 2019). Instead, the disruption by 3D printers has occurred in education and design practice. In education, they have contributed to the emergence of informal learning forms, such as makerspaces. In design studios, 3D printers have enabled rapid prototyping methods that allow for the prompt and streamlined development and testing of prototypes. Yet, as a personal educational technology, 3D printers have brought a new set of affordances and dissaffordances to learners. They afford the sharing and editing of geometry through files at distances; mass production with iterations, which is further accelerated by using artificial intelligence for model simulation; and the geometrical complexity of fabricated objects, and all that without using series of specialized machines and need for safety training. Temporary dissaffordances include the material and functional examination of objects, as the 3D model is translated into a 3D print in a couple of hours. Thus, the adoption and adaptation of technology and the attainment of one's own goals through these mediative properties become the object of research and can be characterized as learning to, by, and through 3D print(ing).

Adopting and adapting 3D printers and attaining goals by using them

Three sets of classifications emerging from postphenomenological were essential for the direct content analysis of the collected qualitative data used in this study.

The first classification addresses skill by technological means, or how learners adopt the technology. This implies the extent to which learners manage to operate the technology and produce the intended immediate results with it. The more they use the technology, the less it obstructs them in their intentions, and the more it becomes *transparent* to them or, the opposite, remains *opaque* to them (Rosenberger & Verbeek 2015).

The second classification addresses inventiveness and encompasses how learners adapt technology to their practice. This refers to the extent to which the technology is meaningfully used for learners' objectives The more they establish practices around the technology to fit their needs, the more it becomes *sedimented* in their routines or, conversely, remains *multistable* or open to a variety of usages (Rosenberger & Verbeek 2015).

The third classification addresses the ability to implement, or how learners apply the technology to affect their environment to attain goals. This refers to the extent to which learners comprehend the possible outcomes of the use of the technology and how it will affect their own mediations with technologies. The more the learners take responsibility for mediations, the more they recognize their agency, changing their *field of awareness* (Rosenberger & Verbeek 2015) and tapping into the *potentiality* of the technology used. In contrast, the more they rely on the existing *field of awareness*, the more they use it in its *actuality* (Kiran 2015).

Results: three course cycles of action research

Research Cycle 1: challenges in constructivist pedagogy

The activities of a learner and a course manager at the department of product design can be described by design studio practice, which Schön (1985) observed and noted:

> *"Given an architectural program or brief and the description of a site, the student must first set a design problem and then go on to solve it. Setting the problem means framing the problematic situation presented by site and program in such a way as to create a springboard for a design inquiry. The student must impose her preferences onto the situation in the form of choices whose consequences and implications she must subsequently work-out all of the field of constraints." (6)*

Thus, for the purposes of this study, I presented students with an existing one-part handheld product as a *site* and instructed them to produce a *design brief* as a *design program* for which they were to analyze this product and critically assess it. From the analyses, they were to *frame the problematic situation*, impose *their preferences*, and test them through a series of physical prototypes, *working out* the *constraints* in material, processes, and functionality. Students were expected to implement and demonstrate new *imposed preferences* with each iterated prototype by testing and reflecting on them.

The focus of the course was students' development as design professionals and their personal approaches to the design process. The pedagogical method relied on individual tutoring, reflective journaling, prototype presentations, and collegial critique. The students were encouraged to manage their own design processes and acquire the skills needed for them. I had previously introduced 3D printing through lectures and live or video demonstrations as an optional technique. My intention was to observe how they could utilize 3D printing in a self managed process.

The overwhelming majority of the 28 students were reluctant to make prototypes. The process took two tutoring sessions and two weeks, during which the students discussed their ideas among themselves, often over rough sketches. Once they started building prototypes, they used techniques learned from the previous courses (See Figure 1). Only four of the students 3D printed their prototypes.

Fig. 1: Starting from the problematic situation and defining preferences, students use the media and materials they are already familiar with, such as wood and metal to answer the assignment. On the image left, preference is gender neutrality, on the picture right is aesthetic congruency.

Revision 1

The notable topic in reflection notes and interviews about the course was students' frustration with pedagogical instruction, which they characterized as incomplete, unspecific, confusing, and contradictory. This topic was also present in their reflections on design activities. Students struggled to formulate what they wanted to achieve with their designs and had difficulties accomplishing them. One learner said, ‘It took me half of the course to understand what the task was really about.’ Another directly addressed the inability to comprehend the expected outcomes of the assignment: ‘It was very difficult to understand what is expected in this course, what are the course requirements, and what should be the effect of our designs.’ This was also pervasive in participant observations, where learners asked for clearer instructions and insisted on practical guidance: ‘What is the right way to do this (assignment)?’ This topic was noted among the students who received top grades but still wondered why their work was perceived as good by teachers.

The adoption of media was mostly about the making of prototypes, such as glazing, gluing, or woodwork. The attainment by means of technologies was described in terms of certain design concepts, such as ergonomics, material construction, and even gender-neutral form semantics, in the context of their user preferences. These topics emerged freely through the learners’ own critical analyses of the site, interests, and prototyping techniques. Accordingly, the students were not describing their designs in terms of intended design goals but as an ongoing discussion with tutors and colleagues and their critiques.

Only four students used 3D printing in their projects. In two of these projects, I found some evidence of adoption and adaptation where leaners had discussed their design processes through series of 3D prints. Regrettably, most of the students failed to adapt 3D printers for their goals.

At the end of the course, the critical friends noticed this disconnect between the students’ intentions and use of media. They assessed that the major issue with the student projects was a lack of meaningful problem formulations or that the problem formulations were not addressed properly in the students’ design activities and prototypes. The critical friends noticed that there was a ‘big split in the quality of the projects’ and that those who did exceptionally well showed great independence in their work. The critique from management was that 3D printers were not used, and that the department did not gain new insights into the 3D printing lab from this course.

The central idea of constructivist pedagogy is to allow learners to decide what and how they want to learn and support them in their own inquiry (Montessori 2013). However, the tension between the quality of autonomous learning and the lack of effectiveness in direction (Sterling 2010) seems to favor learners who are already autonomous. This collides with the values of accessibility to learning, inclusion, and respect for learners’ integrity. Schön (1985) described the relationship between learner and tutor through the model of master practitioner and apprentice in a design studio. I could identify with this model with uneasiness, as I was not teaching students a transparent design practice. Instead, practice was delivered spontaneously, distilled from personal experience, and tailored to the individual learner. This highlighted the issue of power and threatened the prospect of educating critical learners.

According to the literature, the challenges that I met do not seem to be unique. A qualitative study of architecture students in a design studio (Hokstad et al. 2016) portrayed the individual voices of learners and their struggles coping with the ambiguity of the design learning process. Schön (1987) described design learning as a paradox in which students are instructed to learn by simultaneously determining what designing is and how to do it. Thus, according to this idea, my instructions were not only misinterpreted, but they were also unattainable. This is because the learners did not have enough practice performing the task and not enough understanding of design to organize their individual practices. These literature findings led me to doubt this pedagogical approach.

My own research, the input from my colleagues, and the literature review show that the actual challenges the students experienced involved analyzing the existing sites, turning analysis into a problem framework, and adequately addressing this framework through their prototypes. The random and unplanned use of technologies made the learning ineffective, as evidenced by the learners' struggles to materialize their ideas. This indicated that the transition in the autonomous learning processes and the use of maker technologies needed to be pedagogically sustained.

Research Cycle 2: teaching by instructional design

To support these transitions, we taught students digital modeling in workshops and online tutorials before the course started. The course itself consisted of two shorter assignments: an individual one and a group one. The aim of the assignments was to practically demonstrate and pedagogically support the learners' abilities to connect design methods, prototypes, and the problematic situations. Students received a design brief that included a detailed description of how to redesign a generic product to become a personal product for their colleague. We recommended that they conduct an interview with their colleagues, discuss form semantics by using mood boards and a semantic differential questionnaire, and finally iterate ideas through a series of 3D prints. We proposed relevant literature with methods on how to do this.

The second assignment was designed for groups of six students and was introduced as an action research process. Action research methodology was used to break up the framed design problem into observation, action, and reflection to be presented in a design brief. This design brief was missing text but had either images of existing products, mechanical parts generated by 3D printing, or constructions unique to 3D-printing technology. Students were instructed to formulate their own tasks around these manufacturing principles, complete the design brief, and keep modifying it throughout the design process, turning it into an instrument for reflection in their action research. The goal of the assignment was for students to learn how to conduct action research in their own practice and test their assumptions practically through 3D printing.

Throughout the first assignment, I explained the process, teaching them how to conduct and analyze interviews, use semantic differential analyses, and use various techniques when designing objects. Throughout the second assignment, I commented on their action plans in meetings and in the joint design brief posted online.

Revision 2

Students reacted strongly to pedagogical instruction in this cycle as well. However, this time, the learners described the instruction as overwhelming, too detailed, and difficult to follow, especially when relating to the first assignment: 'The instructions were very detailed, and if you don't follow up fast, you easily start lagging behind.' This was especially noticeable in the second assignment when adapting various media to the students' own projects. The detailed instruction was also incomprehensible for some learners, as their own questions were unanswered by the methodology prescribed by the given methods. Students struggled to adapt multiple methods, such as the mood boards, semantic differential analysis, and 3D printing in the first assignment. In their comments, the topics revolved around the appropriate use of mood boards and semantic differential analysis: ‘I was struggling to understand how to use semantic analysis and how those moodboards and adjectives are expected to affect the shape design’.

The other pronounced topic in the direct content analysis was about design activities, as students described their group work experience in the second assignment. As there was not enough time for the adoption process, the students who were not yet competent in digital modeling took on other tasks in the group, such as writing the report, which further diminished their opportunities to become familiar with 3D printing. They claimed that the lack of participation in activities using 3D printing was demotivating. Students for whom 3D-printing technology was not transparent enough seemed to fail to sediment the technology in their practice.

Concerning the adoption of 3D printers, one very pronounced topic was the learners’ struggle to predict the proportions of the 3D-printed artefacts, as they had a ‘different feel of it on the screen’. The other discussion was temporal organization, such as planning when to use 3D printing, as it could be time consuming, depending on the size and details of the artefact. Students also discussed how to optimize their design process to accommodate this issue by printing overnight. This, as well as the mechanical properties of the 3D-printed parts, was a central issue when learners were deciding whether to use other making processes, such as laser cutters, for parts of their artefacts. These topics indicated that 3D printing was becoming more transparent to learners and that new practices were emerging and turning into sedimented routines, realizing student agency.

The critical friends noticed that the students produced more and better detailed prototypes than the previous class did (figure 2). They also noted that more of the students could explain how their prototypes addressed their problem formulations. In this course, the students’ grades were grouped in the middle and upper ranges of the grading scale. In addition, 3D printing became the living practice in this course, and the head of studies initiated moving the course to the very beginning of the first year. The rationale for this was that students need to be exposed to this way of conducting the design process before they get extensive training with various workshop machines.

In the second cycle, the instruction was defined by a curriculum that included topics such as form semantics, product construction, user interviews, and action research as the method. In that sense, learning was defined by the instructional design in formal education and could not be described as learning freed from the curriculum and instructions. The personalized approach to the design process and skill acquisition was abandoned. The students were comprehensively instructed in a variety of skills and introduced to the topics they were instructed to investigate. In the third assignment, learners were provided with a starting point that they had to problematize, media that they had to utilize, and a method for their inquiry.

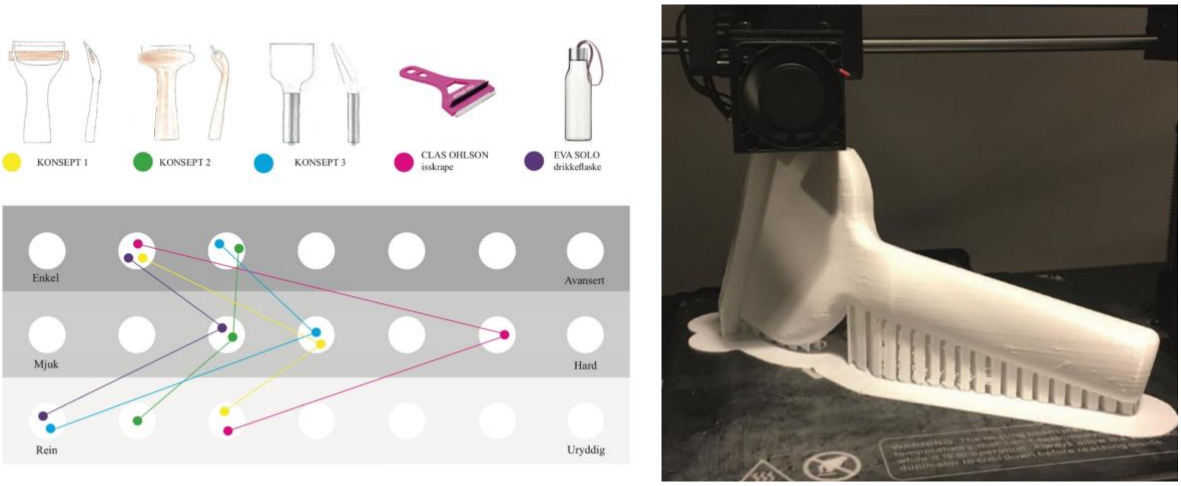

Fig. 2: Example of a two week assignment on form semantics. Semantic analysis and 3D print methods were used as defined in the course instruction.

In this cycle, my role as a pedagogue seemed less personal, as it relied on theory and method rather than on my experience as a design practitioner. I found my work more in line with what Kalantzis and Cope (2010) defined as that of an instructional designer. Instructional design should engage learners in their learning by providing adequate experiences of learning for the intended learning goal. According to some researchers (Halverson & Sheridan, 2014; Martin 2015), emulating a makerspace learning setting in formal education is challenging because of the risk of tool-centrism and curriculum-centrism, which are both problematic for a maker mind-set and an open approach to learning.

Thus, the perceived improvement in results seemed to rely on comprehensive instruction related to the content from the curriculum, which diminished the need for learners to engage in problem framing and hid the incompetencies in 3D printing of the students in groups. This approach seemed to benefit design results more than student agency, as it did not sufficiently expose learners to critical reflection. My colleagues shared a different viewpoint, underlining that it is positive for students' motivation to experience proficient implementation of their designs so early in their studies.

Research Cycle 3: relation and mediation-driven learning

The third iteration of the course was scheduled at the very beginning of the school year. This meant that my colleagues and I had to implement training in digital modeling as part of the course. The course therefore consisted of three assignments. The first included training in digital modeling, and the second and third were repeated from the previous course, with modifications. First, action research was introduced as a method at the very beginning of the course for all three assignments. Second, the course was organized so that the use of 3D printing as a medium in the assignments was predetermined, but the specific use was not. In the first assignment, the students were given sketches of an unfinished abstract artefact and asked to finish it as a digital model and a 3D print. The second assignment was repeated, but this time, it was a group assignment to redesign a product for each other. However, this time, students were instructed to propose their own methodology and implement it in the cycles of action research using 3D printers. The third assignment was modified in two ways. First, the groups consisted of three students, who were instructed to participate equally in the production of prototypes and a brief. Second, the students were not given any content instruction other than to write a design brief before they used 3D printers. The design brief was to document their action research plan, which they fully controlled. To help them accomplish the first assignment, we gave feedback and provided video tutorials to students on how to create digital models. For the second and third assignments, we offered assistance with design briefs for coherence and the practical aspects of the project.

Revision 3

Even though some students pointed out that the instruction was overly detailed and others said it was confusing, the more common opinion was that it was complex, demanding, and difficult. The word 'challenging' was used in multiple instances. They noted a 'steep learning curve' when they evaluated the adaptation of the 3D-printing technology: 'It was challenging but insightful. We found out that many of the things we wanted to make had to be adjusted or discarded in the process.' They also expressed a need for a more holistic understanding of the process in which they were involved: 'I wish I had had a better overview of what we were doing beforehand.'

Students also showed more agency in overcoming 3D printer dissaffordances when adopting this prototyping technique (figure 3). For example, challenges with delayed haptic feedback were repeated in seven of the projects. The learners described this as having to adjust and reprint their artefacts to get the right proportions. Another topic that emerged involved modifying and reproducing digital files on 3D printers with different mechanical material properties.

Fig.3: Example of a two week assignment inspired by affordances and dissaffordances of 3D printers: holder for tablet -flat packed design is fast to print and without support material, while being easy to store and transport.

In the adaptation process, learners struggled to decide what 3D printing as a medium was best suited for so they could take advantage of it in their projects. As in the previous research cycle, the printing time dictated work routines in the 3D printing lab, including printing overnight. When attaining goals through 3D printing, learners took advantage of the ability to distribute digital files over internet sites for personal reproduction and connect to potential users of the product. The other commonly noted topic for using unique 3D-printing techniques involved complex geometries, such as enclosed hinge systems and Voronoi structures. Finally, some of the students talked about how they researched on the internet to learn more about the application of 3D printers.

In the third research cycle, the instructions were aligned with the classifications informed by postphenomenology. The assignments were designed to support learning from adoption to adaptation and attainment. In the first assignment, I supported adoption by sedimenting the purpose of the 3D printer and providing a sketch so that learners could gain transparency of the tool. In the second assignment, I encouraged experimentation by providing a social context but not giving a precise purpose of the tool, letting learners explore its multistability. In the last assignment, by focusing on the construction of the objects, learners had to use their sense of transparency and the multistability of the tool to contemplate possible constructions for their designs in teams.

In this research cycle, my role as a pedagogue was still based on instructional design. However, the instructions were aligned with the sociotechnological environment of the studio rather than the curriculum or learner-defined inquiry. Tutoring was also based on discussion about what could be done with 3D printers and entirely left out design critique.

My colleagues evaluated the results of the projects in terms of accomplishment and quality, similar to their process for the previous course. The grades declined slightly toward the middle of the scale. The research material showed that students were more engaged with 3D-printing techniques, as the strategic use of their affordances was more pronounced.

Example of learner–technology mediation in a design course

Most of the data sets included personal reflections or discussions in which learners evaluated different aspects of the design challenge through a series of design proposals. In the data sets, the classifications were shifted interchangeably. The classifications also appeared on two levels in the context of the usage of the 3D-printing technology as well as on the emerging technology that the learners designed.

Learners explained their chosen task through the changed field of awareness and technologies' potentiality: 'We wanted to use 3D printing to make fasteners because we can make them complex, test, modify, and reproduce them quickly.' They assessed the multistability of the newly invented fastening technology: 'Clips could allow modifying the storage; it could be modular.' They discussed the new modular clipping technology and its potentiality: 'We want to design a system for storing clothing, but we haven't landed on that yet.' They further discussed how this could be done by 3D printers, sedimenting 3D printing into their own practice: 'We will 3D print clipping modules that hold the plywood structure.' Finally, they turned this into comprehensible instruction: 'The most important thing in the first round is to make sure the modules hold the structure, and they are easy to mount and demount for one person.' They further discussed how transparent this new modular shelf technology could be: 'We will not have time to test this on users. We cannot claim it is easy to adjust the shelves.' Finally, they created a more comprehensible and manageable task: 'Let's make a modular bookshelf that you don't adjust too often but can fit in any interior. We can then demonstrate different shelf configurations' (see Figure 1). Their design and learning topics were defined by the allowances and prohibitions of the fastening technology, as was the new practice that emerged from the mediation between learners and 3D printers.

Fig. 4. Modular shelf system made by a group of six first-year students in two weeks.

Discussion: alternative pedagogical framework for the design studio

This study exemplifies the challenges of inciting maker pedagogy in formal education such as design studio. The challenges for learners involve the lack of experience in organizing one's own project-based learning. The challenge for pedagogues is generating open learning inquiry without falling back on tool-centric instructionist or curriculum-centric approaches. Through iterative action research, this study provides a critique of and an alternative to constructivist theories, especially regarding the lack of explanation about the role of technologies in learning and the transfer of the responsibility for learning to learners. Thus, a step forward in pedagogy was visible when the given instructions evolved from problem framing and design specifications to the technical affordances of 3D printers. When it comes to responsibility for learning, this study indicates that, when pedagogical instructions are more aligned with the social and technological environment rather than predetermined content or process in the design studio, they become more comprehensible to learners. Regarding the role of technology in pedagogical instruction, this study demonstrates how tool-centric instructionist approaches can be expanded beyond skill acquisition toward adaptation of and attainment through technologies and could be an alternative to constructivism and constructionism. This study provides a new perspective on design studio pedagogy for the future, where the influx of novel technological media, its utilization, and the development of new technological practices will become more important. It illustrates how networked technological learning, common for learning at work can be applied in formal education.

Content and instruction in maker pedagogy

Let us return to the questions posed in the introduction regarding on the choice of content and instruction in maker pedagogy in a formal educational setting. In maker pedagogy, media affordances and the social context, rather than curricula or the prescribed processes, determine what is going to be learned. If pedagogues want to introduce specific content, they should introduce new actors into the course, such as a specific user and client in the design studio, or a member with different preferences in makerspace rather than only new literature or group activities. Students would have to engage with topics characterized by the needs of these actors to realize their own agency. In the repeated design courses in this study, students' own interests and design inquiry were framed by the affordances of 3D printers and their social groups, much like in makerspaces. Some of the student groups connected to external networks; for example, one group decided to distribute their product through a website for digital model sharing, where they engaged with a group of users who provided feedback.

When it comes to pedagogical instruction in maker approach in formal education, the role of pedagogy is to support learners' own agency and awareness rather than their acquisition of skills or construction of knowledge. Learners' agency directly depends on their sense of technological transparency, and pedagogical instruction must incorporate issues of the learners' technological environment. While technology is opaque to learners, instruction is meant to support their persistence in mastering it. Once the technology becomes transparent, instruction is meant to support learners' ability to make decisions independently. Therefore, to be understandable and attainable, the instruction must encompass learners' sociotechnological environment rather than only curriculum topics or the process. In a future with a workplace characterized by the influx of new technologies, the goal of maker pedagogy should be the ability to realize one's own agency through technologies and the responsibility for one's own doings.

In this sense, a pedagogue becomes a facilitator of the sociotechnological environment. From the postphenomenological perspective, by bringing 3D printers into the classroom, a pedagogue is setting the meditative properties of 3D printers as a precondition for what can be learned and how. Learners in the design studio do not just use 3D printing to produce experiences and construct knowledge; instead, they use 3D print artefacts for a certain purpose. The 3D printer therefore mediates between them and their design intentions and sets the learning stage in which the social activity around using and utilizing 3D printers becomes the focal point of learning. In doing so, the set of technologies, including digital modeling, layer slicing software, and, finally, the 3D printer, helps shape the subjective experiences and objective reality for learners.

Conclusion: Technologically mediated pedagogy in formal education

Postphenomenological perspective enables discussion about pedagogical challenges in design and maker contexts that does not solely rely on curriculum, instruction, and knowledge outcomes in formal education. Design and maker pedagogy seen from the postphenomenological perspective does not need to be framed by learners' critical reflection and design critiques by peers. Instead it is framed by what technologies can do and most importantly, what the needs of the learning network are. Design and maker pedagogy can be relationalist in the sense that the pedagogical intervention is directed toward human–human and human–technology relations rather than learners' construction of knowledge. This approach relies on the sociotechnological network to develop content, questions, activities, and suitable sustainable practices with technologies through a consensus generated by trial and error rather than on a design critique or curriculum plan.

Design and maker approaches in formal education beyond the design studio can occupy a niche between formal training, practice placements, and academic courses. This can be particularly beneficial in formal institutional settings when related to labs, workshops, and multiple actors, such as master's students who are involved in research projects. The benefits of maker pedagogy in formal education, compared to the abovementioned educational forms on the one hand and informal makerspaces on the other, are in the inclusion of learners on different levels and interests, as well as project process methods and critical awareness of one's own actions using technology.

This also makes it possible to describe design and maker approaches through the European qualification framework for course design. The framework provides an explicit and precise description of the knowledge, skills, and ability of the learner to apply these knowledge and skills autonomously and with responsibility (EURspace, 2019). Maker pedagogy emphasizes learners' autonomy and responsibility, which is defined in relational terms, that is, by the role learners take and the learning environments they occupy, rather than their skills and knowledge. Moreover, the instruction can be used to support the responsible use of technologies. As a variety of multistable, versatile technologies with high potentialities, such as artificial intelligence and mixed reality, continue to enter work life and classrooms, learners' agency will become increasingly important. As learners are supported by technologies, they will progress faster through intended learning outcomes and will also need to become more responsible in how they use these technologies. It is therefore essential to position maker pedagogy in the context of universities' role in facilitating learners' integrity and resilience (Levin & Greenwood 2008). In the end, these learners will be the ones who will have to cope with sociotechnological disruptions and who should think critically about the affordances, limitations of technologies and emerging ethical challenges when implementing sustainable development.

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