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39.3 3D Printing in the Wild: Adopting Digital Fabrication in Elementary School Education

**Teemu Leinonen^{id}, Marjo Virnes,
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Abstract

In recent years, digital fabrication, and especially its associated activities of 3D design and printing, have taken root in school education as curriculum-based and maker-oriented learning activities. This article explores the adoption of 3D design and printing for learning by fourth, fifth and sixth grade children (n=64) in multidisciplinary learning modules in elementary school education. School-coordinated 3D projects were not led by design experts, such as art and design teachers, designers, researchers or technical specialists, but run 'in the wild' by school teachers. The study was conducted by using an ethnographic research design, including field observations, non-formal interviews and a reflective questionnaire. The results indicate that, in the adoption of 3D printing activities, learning is centred on the technical skills and the usage of 3D tools. Hence, the elementary ABCs of 3D printing do not achieve the full design and creativity potential of digital fabrication that earlier research has suggested. However, the results do have implications for the potential of 3D printing projects to increase children's empowerment. In their current state, 3D design and printing are some of the learning tools, among others, and similar achievements can be achieved with other hands-on learning technologies. In order to enhance the learning of creativity and design thinking skills, 3D activities in school should be planned accordingly.

Keywords

digital fabrication, 3D printing, elementary education, design, multidisciplinary learning, making

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Introduction

In the last ten years, computer numerical control (CNC) machines, robotics and the design tools used with them have undergone a change. The development is similar to the evolution of mainframe computers to personal computers (PCs) in the late 1970s. In the same way, digital fabrication, including activities such as 3D design, modelling and 3D printing, has become a readily available tool for learning at schools (Lipson & Kurman 2013). As computers, educational robotics and many other learning technologies have opened up new possibilities for children's learning, 3D printing is also claimed to renew learning to the same degree (Eisenberg 2013; Eisenberg 2004; Gershenfeld 2005). While easy-to-use programming tools and educational robotics designed for children have shaped the teaching and learning of Science, Technology, Engineering, Arts and Mathematics (STEAM) subjects and so-called computational thinking (Papert 1993; Tedre & Denning 2016), digital fabrication has enabled design thinking and personal artefact production (Gershenfeld 2005). Both tracks provide opportunities to design, invent and produce artefacts, and thus, raise curiosity and motivation to learn about diverse subjects (Lipson & Kurman 2013).

In Finland, where this study was carried out, both art and crafts education are included in the school curriculum as compulsory school subjects from the first grade (7 years old) up until the seventh grade (13 years old). Art, crafts and making are recognised as essential activities both in the latest National Core Curriculum for Early Childhood Education and Care (Opetushallitus 2016) and in the tradition and practice of kindergartens. Furthermore, following the spirit of the Educational Sloyd movement started by Uno Cygnaeus in Finland in the 1860s, these activities hold a significant value. In this tradition, handicraft-based education is considered a means to attain general educational objectives such as building the character of the child, industriousness, higher intelligence and moral behaviour (Reincke 1995).

Art, design and craft education, however, are not the only platforms for applying digital fabrication to learning. In school, 3D design and 3D artefact production are often curriculum-based learning activities that combine, for instance, arts, crafts and STEM subjects in multidisciplinary learning projects. Multidisciplinary learning modules address a selected theme from the perspectives of several study subjects. The latest Finnish National Core Curriculum for Basic Education (Opetushallitus 2014) encourages teachers to engage with multidisciplinary and participatory learning with integration and dialogue between study subjects. New technologies and digital fabrication bring forth self-designed projects, and thus empower children as learners by making. Contemporary Finnish art, design and craft education echoes the ideas presented in recent studies. For instance, instead of merely being taught the use of quickly outdated technical equipment, designing their own projects and products is expected to enable children to develop their interests and creativity, as well as computational literacy skills (Blikstein 2013).

The school context has given rise to concerns about whether curriculum-based learning activities can fulfil the art and design philosophy, empowerment and democracy of the maker culture (Blikstein 2013), and whether the potential of digital fabrication that has been recognised by many researchers can be accomplished in the school environment (Nemorin & Selwyn 2017). Halverson & Sheridan (2014), for instance, point out that the maker movement and culture has its roots in Deweyan constructivism and Seymour Papert's ideas of learning with embodied,

production-based experience. Accordingly, Blikstein (2013) draws on Dewey, Papert and Freire and declares making in education to be student-centred and interest-oriented, whereby the construction of knowledge is connected to culturally meaningful real-world objects and problems.

This research was part of a project in which an elementary school aimed to refresh existing learning practices by using the ABCs of 3D design and printing. In the school-coordinated project, schools and teachers were free to plan their own 3D design, modelling and printing activities. Because of the multidisciplinary character of the activities, pupils were not directed to focus on specific subject content but to develop a multidisciplinary set of knowledge and skills. Drawing on the work of Callon (Callon et al. 2001; Callon & Rabeharisoa 2003; Callon 2003), the setting made it possible to explore digital fabrication 'in the wild' — in real school environments where experts did not take the lead, but the teachers, the practitioners, designed their own teaching experiments.

The research setting enabled the investigation of the following question: 'How does an elementary school adopt 3D design and printing in the context of multidisciplinary learning?' The present research aims to create a big picture of 3D tool use in the classroom, its opportunities, and obstacles. An ethnographic research approach, where a researcher participated as a passive observer in the 3D design, modelling and printing sessions at the school, was a methodological choice for understanding various aspects of adopting 3D tools for education.

Digital fabrication in education

Previous research has shaped today's school education by developing pedagogical and technological designs for better learning. Contemporary pedagogical thinking (Gershenfeld 2005; Harel & Papert 1991; Papert 1993) has launched the direction in which technological development has enabled visionary thoughts on learning (Eisenberg 2013; Eisenberg 2004) and in which pedagogically justified designs have directed the use of technologies (e.g. Harel & Papert 1991; Iversen et al. 2016; Katterfeldt et al. 2015). Digital fabrication and its roots in constructionism (Harel & Papert 1991), learning by making, and the advanced and inspiring technologies, have recently been integrated into school education. It is also claimed that extending the maker movement and elements of its culture into education could further improve learning at school (Dougherty 2012; Martin 2015). Next, these perspectives are presented to give an overview of the theoretical background of the present research.

Maker culture in education

In the maker culture (or, the maker movement), people are acknowledged as *makers*. With a dose of enthusiasm and excitement, these makers utilise technology and digital tools in creating and learning new things and artefacts. This loose community shares a passion for mixing the fields of art, science, crafts and engineering – without, however, employing an economic agenda. The culture is formed around Internet forums and sites, the Make magazine, and the Maker Faire events, where innovation is reported to occur unfettered, and also, take place 'in the wild'. Maker culture could potentially be extended to schools and education: doing, making and

tactical assignments help students to engage in the learning process, and a concrete outcome, an object, is a proof of learning that encourages personal storytelling (Dougherty 2012).

Researchers have raised questions about the ability of school education to adopt the philosophies and theories of maker culture, and to apply digital fabrication and tools, in order to achieve similar outcomes to those achieved by the international research community (Nemorin & Selwyn 2017; Iivari et al. 2017). While multiple studies have concentrated on extracurricular activities, inquiries into the maker approach as part of classroom activities are still lacking (Papavlasopoulou et al. 2017). Consideration of the foundations of digital fabrication and maker culture in education has been called for (Burdick & Willis 2011). The concerns are relevant, as school education wishes to adapt maker culture to learning environments that currently rely on STEAM and twenty-first century learning skills without the perspective of art and design education. Also, the elements of maker culture, such as making that stands for activities, maker as an identity, and makerspace as a community of practice (Halverson & Sheridan 2014; Blikstein 2013; Burdick & Willis 2011), should be taken into account in the school environment. Maker culture could offer several opportunities for education, but schools cannot rely on adopting digital tools alone. It is equally important to introduce the maker community infrastructure, which supports the development of expertise, as well as the playful maker mindset, which encourages sharing, collaboration and dealing with failure (Martin 2015).

3D projects in school education

In spite of possible cultural differences between the maker culture and the school culture, making in forms of digital fabrication, such as 3D design and printing, has been widely established in schools. Very few studies have explored the topic with an attempt to understand the challenges of changing school culture in this area. In their ethnographic study on a 3D printing course in an Australian high school, Nemorin & Selwyn (2017), however, concluded that 3D printing in schools is a complex issue, and as a practice, it should be treated as any other technological equipment. Instead of innovative, learner-centred ways of learning, the application of 3D printing yielded processes that reinforced traditional educational practices, such as behaviourist forms of instruction and training, a restricted learning environment and the teacher as an expert.

According to a survey on the impact of 3D printing projects on learning, teachers reported that pupils developed digital age skills such as 3D modelling, creativity, problem-solving and technology literacy while working on the projects (Trust & Maloy 2017). Similar conclusions about the improvement of technological literacy and creative capacities are made in a study on open source 3D printing and design activities in the high school environment (Kostakis et al. 2015). A study on 3D design, modelling and printing in history and social studies classes suggests that despite the challenges of using new technologies and connecting 3D activities to curriculum topics, pupils learned actively and expressed their ideas in new ways (Maloy et al. 2017).

Call for evidence-based understanding

Previous studies have investigated children's interaction with learning tools (e.g. Christensen & Iversen 2017), the theoretical and philosophical context (e.g. Papert 1993; Harel & Papert 1991; Blikstein 2013), school learning and pedagogical practices (e.g. Angello et al. 2016), and opportunities and obstacles (e.g. Buehler et al. 2014). Furthermore, it has been recommended that the investigation should be evidence-based (Papavlasopoulou et al. 2017). Of course, these visionary thoughts have transformed education the most, but evidence-based outcomes have provided a valuable understanding of the real-life context. In that sense, it is necessary to understand the actual phenomenon in order to make it applicable to the school context.

With this research, we aim to enrich the existing literature with an empirical understanding of the adoption of 3D printing in schools. An ethnographic research approach was applied to study the use of 3D design, modelling and printing tools 'in the wild': in a classroom without researchers introducing any lesson plans that the teachers and pupils would be expected to follow. In other words, the school and teachers planned and executed the activities independently. Hence, we were able to explore the entire phenomenon from various perspectives; starting from the children's interaction with the tools to the school culture, practices and pedagogy. Moreover, it was possible to outline the challenges and opportunities related to the use of new technological tools in schools.

Research design

By using an ethnographic research design (Genzuk 2003; Pole & Morrison 2003), we aimed to result in a narrative description of the integration of digital fabrication into school education. One of the authors was responsible for the fieldwork, which included observing students working with the projects and conducting informal interviews with teachers. The researcher was both an insider and an outsider: she was another adult in the school alongside the teachers and other staff members, but also stayed aside of the student groups working on their projects (Genzuk 2003; Pole & Morrison 2003) When working on the research materials, the theoretical ideas on constructionism, maker culture, and making and digital fabrication, framed the analysis and allowed to reflect descriptions and explanations.

Research participants

Altogether, 64 school children in the fourth grade (n=17, age 10), fifth grade (n=23, age 11) and sixth grade (n=26, age 12) and their class teachers (n=4) from one elementary school participated in the study in an ordinary school following the Finnish National Core Curriculum. Children were studied as groups based on their grade level, which minimised the impact of previous individual experiences. Moreover, this kind of a heterogeneous group could be seen to represent any group of school children, which made the research setting realistic.

Learning activities in the classroom

The school's goal was to bring new digital technologies to school education, and thus open up new ways of learning to children. By renewing curriculum-framed learning practices, the school aimed to support a learning culture that increased children's competence in multidisciplinary areas of learning, from specific subject knowledge to self-esteem and empowerment. The school and the teachers had some previous experience in using technologies and doing project-based work, especially in STEAM. Therefore, digital fabrication with 3D model design by Tinkercad software and 3D artefact printing by Ultimaker printer were reasonable choices.

Learning the ABCs of 3D design, modelling and printing took place every second week for a period of two months. The fourth and fifth grade pupils had four 2 x 45-minute sessions, and the sixth graders had five 2 x 45-minute sessions. Due to the schedules of the school, the number of sessions varied. The content of the 3D project was similar for all grades. As an extra activity, the sixth graders carried out a so-called 3D driving licence that tested the Tinkercad 3D modelling skills. The children completed the test in pairs: one performed the 3D tasks by Tinkercad, while the other monitored the correctness and fulfilment of the tasks.

The 3D project consisted of the ABCs of 3D design, modelling and printing. The session series started by familiarising the children with the 3D printing industry with inspiring 'wow' effect examples. Next, the basics of 3D modelling were introduced with the Tinkercad design software. Properties such as adding shapes, grouping and alignment, were used for completing the first design tasks. These design tasks, which were similar for all grades, required mastering the basic design software properties and artefact design skills based on the given specifications, such as designing a name tag, a floor plan and a game piece. The role of self-design increased as the 3D project proceeded, with the final task being the design of a utility product. Although the design topics, such as game pieces and utility items, were the same for everyone, the fact that the 3D designs were individual was aimed at getting the children to apply their own ideas and inventiveness. Figures 1–3 illustrate the 3D design tasks.

Research data and analysis

Research data were collected from non-formal interviews, field study observations, a questionnaire (available at: <https://legroup.aalto.fi/wild-questionnaire>), and documents, such as teaching materials and digital photos of the process, during a total of thirteen 3D modelling and printing sessions at school. The participating children were the main informants in order to make children's interaction with 3D technologies visible, and allow the children's voices to be heard. Every child, and his or her teacher, was interviewed during each session by using semi-structured interview in an informal and relaxed environment. The interviewer took notes and audio recorded the interviews. The insights from the interviews were further discussed with teachers to defining the context and the aims of the pupils' projects. Field notes were also written during session breaks or directly after the session to document initial observations in as much detail as possible. Audio recordings of the interviews and discussions with the children documented and supported the field observations. A short reflective questionnaire aimed to surface children's individual

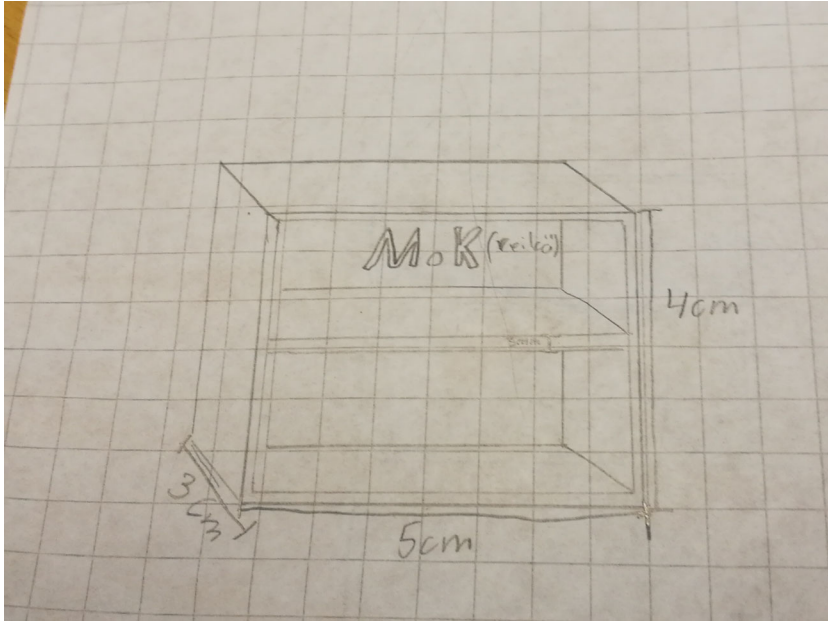


Figure 1
Utility item design on paper

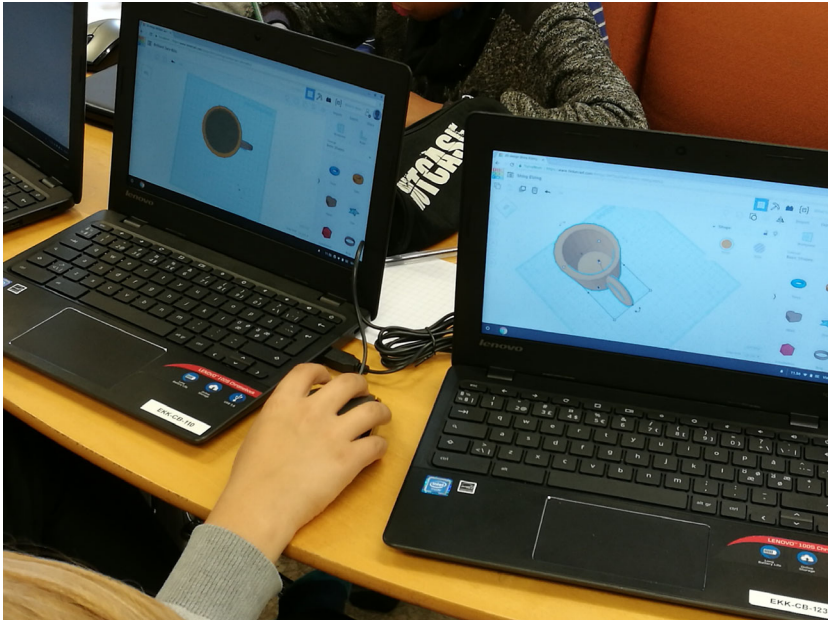


Figure 2
3D modelling on Tinkercad design software

thoughts during the design and modelling process, whereas the field observations revealed their external behaviour. The questionnaire, which otherwise played a minor role during the sessions, was also intended as a tool for the children's

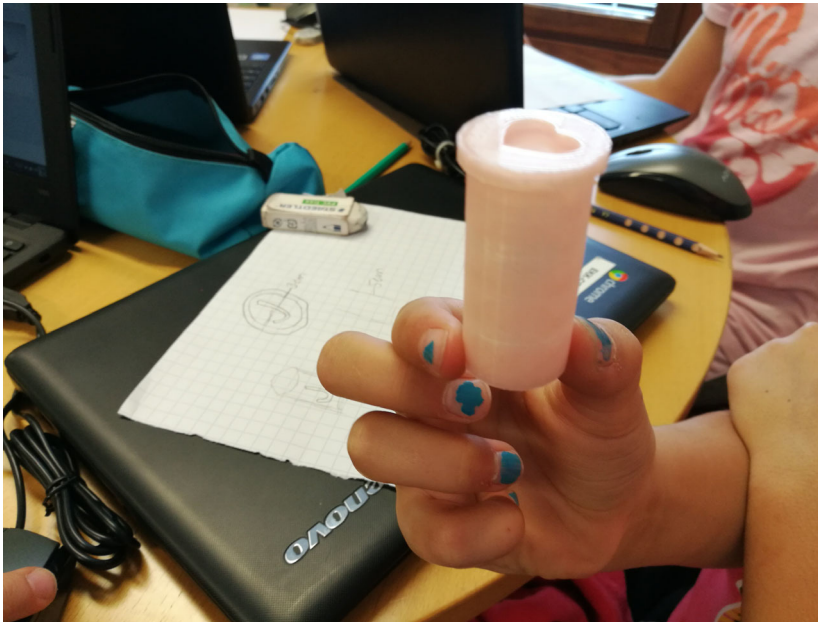


Figure 3
3D printed artefact

learning and reflection. That is, the purpose of the questionnaire was twofold: it supported the children's learning and provided the data for the research. In the questionnaire, the children (1) described the topic they were working with, (2) named two successful features at that moment, (3) named two features to be further developed, and (4) named their best experience with the 3D project so far. The questionnaire was an online form that children were asked to fill out while in the classroom.

The analysis categorised the materials from the questionnaire, interviews, field notes and other documents with open coding (Flick 2009). The key findings were identified through open coding and categorising the concepts. Furthermore, in the analysis, we reflected on the materials in light of theoretical foundations and the empirical research outcomes of maker culture and digital fabrication in school education in terms of tool use, creativity and empowerment. From the material we produced quotations, descriptions and excerpts of documents, resulting in the final narrative description.

Findings: 3D printing in the wild

Based on school teachers' and children's experiences and the numerous 3D artefacts completed by every child, the 3D project was a fruitful learning experiment. It introduced 3D design and printing to the children, who were able to create 3D artefacts by themselves, make mistakes, learn from them and experience success. The software and 3D printers were fairly easily adopted as tools. Furthermore, the children's thoughts and reflections on the 3D design, modelling and printing demonstrated their interaction with 3D tools and, by implication, the role of the

children's creativity and empowerment in the process. According to the teachers' observations, the 3D project aroused curiosity and generated motivation – even for those children who showed little motivation for learning in other school subjects.

Although it is indisputable that children learned during the project, it is interesting to delve a bit deeper into the research data to look at *what* they learned. With this exercise, we aim to reflect the findings in light of the research literature.

3D printing for technical skills

The learning activities focused on the ABCs of 3D modelling and printing in order to provide children with basic knowledge and skills. Indeed, in their reports, the majority of the children mentioned technical skills either as areas of success or as something to be developed. 3D design, modelling and printing emerged as tools for constructing and using knowledge in different formats, for instance, by presenting the abstract concepts of shapes in digital design and transforming digital designs into physical artefacts. Design activities, problem-solving and mathematical skills run through the process but, due to the relatively simple nature of the tasks, remained facile. The research literature claims that these types of activities were a good method to integrate different school subject, but in this case it did not happen. The issue could be addressed by guiding students to work on project that include more clear science and maths problems, such as related to the size and volume of objects or density and use of material.

Mastering the design software properties was mentioned in the reflections mostly as a successful matter. In the children's reflections, the learning tool appeared via its properties and children's skills in using it, for example: 'I should be able to turn the shape around and adjust it to the right position' and 'In my mind, I was able to group and align items well.' Interestingly, these technical skills were mentioned again in the matters requiring further development, for instance: 'I could do better with zooming' and 'I should use more measures.'

3D printing for creativity and design thinking

As the learning activities focused on the technical skills of 3D modelling and printing, the activities had an impact on to what extent the children were able to utilise their creativity and develop design thinking. Task-based designs did not enable the full potential of creativity that 3D printing activities are expected to provide, but to some extent encouraged the children to make their own designs and inventions.

Classroom observations and the children's reflections indicated the children's willingness to create self-designed artefacts, even though following the instructions is equally relevant in certain situations. Self-made designs and artefacts were emphasised in some cases when reflecting on the best experiences: the best thing so far was 'when I created and designed artefacts by myself'. When inventing ideas caused a problem, children named 'design and that I could invent more by myself and could be more creative' as targets of further development. Design details of the artefact were also mentioned: 'I could add more shapes and design one shape of my own.' The final products included the evaluation of the artefact: 'In my

opinion, I succeeded in creating a good shape for my game piece and making it practical.'

The novelty of having the opportunity to design and produce something concrete – a physical artefact – makes 3D printing different from many other uses of computers and computer technology in education. If compared to the widespread use of PCs in schools, the 3D printing activity is closer to learning programming, digital image and video editing, and digital storytelling. With 3D printing, the fact that there is an outcome, which would be impossible or at least very difficult to create without computer tools, raises children's interest in imagining what they could do with the tools.

3D printing for empowerment

According to Gershenfeld (2005), empowerment lies at the heart of digital fabrication through its potential for independence, imagination and intellectual freedom. The findings reflect on empowerment as learning and competence development to gain skills to prosper in a digital environment (Iivari & Kinnula 2018; Kinnula et al. 2017). The 3D project seems to have offered these possibilities. Children mentioned the best things in the project were that 'I used my own creativity and there was a possibility of doing almost anything,' 'I was allowed to choose what to do' and 'The only limit was imagination.' In this study, the appreciation of self-designed artefacts, together with learning new knowledge and skills, were elements that implied the potential of 3D printing projects to increase children's empowerment. The children's pride in their 3D designs was revealed throughout their reflections on successful matters: 'I think the name tag was truly great.'

In the present experiment 'in the wild,' empowerment through social interaction, such as knowledge sharing and collaboration, was moderate. Research on teacher–student interaction in technology-supported classrooms shows that technology, in its many forms, can support new opportunities for more in-depth interaction, both in face-to-face classroom teaching and online (Harper 2018). On only one occasion, a child named peer learning as one of the success features: 'I helped my classmate.' Success, however, was experienced when working autonomously during design and modelling, for example: 'I managed to create all the shapes and I didn't need to ask for help from adults.' Hence, some pupils learned self-management skills.

Printing a physical object that holds personal meaning offers potential for empowerment (Schelhowe 2013). Therefore, an empowering learning experience could stem from holding the self-fabricated artefact in hand and giving it a name. For some children the best thing was to 'get a 3D artefact to myself and take it home', and others straightforwardly named 'name tag and fidget spinner' and 'airplane and table' as the most successful features of the 3D project. The creation of physical artefacts by 3D printing shares similarities with Educational Sloyd; children working with 3D modelling and artefact fabrication get a first-hand and, at some level, embodied experience, of having an impact on the world. Furthermore, 3D modelling and printing in schools resembles digital storytelling activities. In particular, the recent additions to programming, digital storytelling, and digital image and video editing platforms that enable pupils to share their creations online with others have made it possible for children to share their images, stories, animations

and games with their friends, and build new relationships with like-minded children in other places.

Conclusions

Initial findings from the ABCs of 3D printing project revealed similar opportunities and obstacles to the internationally reported research on 3D printing projects (Angello et al. 2016; Blikstein 2013; Buehler et al. 2014; Christensen & Iversen 2017; Eisenberg 2004; McNally et al. 2017; Maloy et al. 2017). The children focused on mastering software properties and other technical skills, and they encountered issues with the usability of the computer tools. Predefined tasks were occasionally perceived as 'tasks only', leaving ownership of artefact production weak. These factors, along with a too-tight timetable, caused frustration among teachers and students in the classroom. At the same time, the children still designed and created self-made artefacts and expressed satisfaction with hands-on and 3D printing work.

The findings were consistent with many other learning technologies that emphasise hands-on learning activities, problem-based learning and knowledge construction with physical, real-life artefacts (Alimisis 2013; Benitti 2012; Iversen et al. 2016). Hence, these similarities pose some questions about the additional value of 3D printing projects in education and the positive changes that 3D printing can bring about in school education.

First, in spite of similar advantages of other learning technologies, school education holds a position on 3D printing without exaggerating its benefits and perhaps even constraining its use as a tool (Nemorin & Selwyn 2017). 3D printing is a tool among others, taking its position in the multidisciplinary learning projects of art, design and crafts, where complex artefacts can be created by 3D printing.

Second, art, design and craft education, where the use of design methods has a long history, plays a key role in adopting 3D printing activities in school education and implementing the philosophy of digital fabrication and maker culture. Design and aesthetic endeavours related to making enable students to incorporate individual and personal identity into the artefacts (Halverson & Sheridan 2014). As robotics and coding have challenged elementary schools to get a grip on the new domain of computational thinking (Tedre & Denning 2016) and programming platforms, digital fabrication challenges schools and teachers to strengthen the role of design thinking and methods (Iversen et al. 2016; Smith et al. 2015; Hjorth et al. 2016), including iterations and reflection, in multidisciplinary learning projects.

To teach through art and design processes with digital fabrication, teachers need to learn new skills, such as grasping complex design processes, mastering both digital technologies and analogue materials, and balancing different modes of teaching to avoid losing control of the class (Hjorth et al. 2016). Teachers should also offer strong instructional guidance when teaching learners from novice to intermediate levels, despite the popularity of providing minimal guidance, for instance, in science education (Kirschner et al. 2006). Discussing Kafai et al. (2014), Halverson & Sheridan (2014) state that making can also challenge our traditional conception of what constitutes a learning activity. For example, e-textiles combine 'hard' and 'soft' skills in a novel way. Thus, digital technologies do not reduce the need for craft skills but actually require traditional art, design and crafts education in modern learning.

Third, 3D printing projects at schools include all the potential that the research community has addressed, but fully adopting them requires increased competence in tool use, pedagogical design and understanding the maker movement and maker culture (Burdick & Willis 2011; Martin 2015). In our study, the 3D design, modelling and printing experiment with the approach of letting teachers themselves decide on the activities, resulted in relatively elementary ABCs of 3D printing and did not achieve the full potential for creativity and design. To reach the special value that the earlier research has indicated 3D printing activities may have for school learning – emerging via art, design and crafts education and elaborated design thinking – would require a comprehensive cultural change in a school.

For instance, according to Halverson & Sheridan (2014), engaging in learning activities does not automatically create a sense of community, as the maker community seems to emerge rather than being formed. In the maker culture, the communities of practice also share a range of activities unrelated to making. In these communities, learning happens, but it is not guaranteed or regulated. Individual freedom and personal interests play a significant role in makerspace learning. Instead of focusing on individual learners, the key area in incorporating makerspaces into formal education could be 'how to design the space to enable distributed expertise and open configurations of learning' (Halverson & Sheridan 2014, 502). The schools' 3D printing spaces could more closely resemble art and makerspaces, as well as be operated according to the practice of the makerspace communities. In addition, reaching out to the out-of-school maker community could also provide additional value – with existing practices of taking advantage of online resources and organising events that spark inspiration – and allow children to develop their expertise outside the school context (Martin 2015). To some extent, children are already exposed to the maker community through extremely popular video tutorials on social networking sites (e.g. 5-Minute Crafts – a YouTube channel with close to 33 million subscribers). Rather than diverging from the outside world, school education might want to incorporate some of the maker culture elements to enhance learning by making. In schools, new computer tools – from desktop computers to tablets, robotics, coding and 3D printing – should be taught and put into use in a real-world context, in relation to children's everyday culture. In this way, schools may prevent children's alienation from the school's reality.

Discussion

In this ethnographic research, we explored how an elementary school incorporated digital fabrication, in the form of 3D design and printing, into their activities and how it supported the idea of multidisciplinary learning. Our results indicate that teachers were able to introduce the technical skills related to 3D design and production to their pupils through instructions and assignments. In the projects, there were some elements of multidisciplinary. To see how the digital fabrication will finally be integrated into the daily activities of the school and how it will (or will not) support multidisciplinary learning would require a longitudinal study.

Furthermore, we have studied how digital fabrication tools and activities, specifically 3D design, modelling and printing, achieved advantages that earlier research has asserted to be provided by digital fabrication. In this case, pupils did not become profoundly involved in creativity and design thinking and therefore did not learn many of these competences either. To achieve them, the projects should

include more time for pupils' ideation, sketching and prototyping. These tasks should be discussed and formatively assessed throughout the process by the teachers and their peers and the designs should be iterated according to the feedback. The pupils, however, expressed feelings that are related to experiencing empowerment. Pupils said that they learned they could implement various ideas and designs with the skills of digital fabrication.

In this research, we investigated whether digital fabrication in general could produce change and, if so, what the reasons were behind the changes. In our case, digital fabrication, in the form of 3D modelling and printing, turned out to be one learning tool among others that enable moderate design, creation, hands-on activities and a self-made end product. In a similar way to other technical skills that are learned in art, design and craft classes, the pupils' project with 3D tools aroused feelings of empowerment, engagement and joy at the self-designed and self-produced artefacts. When compared to already existing art and design activities in Finnish schools, the impact of digital fabrication in these areas was not unusual, except for the case of empowerment.

In recent years, art and craft education in Finland has gone through some major reforms. Two study subjects, technical work and craft using mainly textile, were merged into one subject taking advantage of various materials. Programming, digital design and digital fabrication fit very well to the new subject, but at the moment it is still too early to see what kind of practices in schools will merge on top of the long tradition of art and craft education.

However, based on this research, to have more creativity and design thinking activities and skills following on from those, 3D modelling and printing activities in schools should be planned accordingly. In the experiment 'in the wild', these activities did not emerge independently. Instead, teachers' and pupils' main focus was on learning technical skills related to digital fabrication. Here we see a need for more research, teachers' professional development and teacher training. Moreover, further research is also required to assess whether introducing art, design and craft education practices, the maker philosophy and makerspace learning environments to teachers and schools could enhance creativity and design thinking in 3D printing projects. However, as the results manifest the empowerment of pupils – in a different manner when compared to traditional art, design and craft activities producing artefacts in schools – the 3D design, modelling and printing activities defend their place in a school curriculum.

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Selection and participation of children

Research was conducted as part of a school-coordinated project that aimed to introduce 3D modelling and printing to school education. Children in grades of four, five and six at one elementary school participated in the research together with their class teachers. The whole class of children from each grade participated in the study, thus no other selection process was conducted. Children's

participation was based on voluntary and informed consent. The consent form included descriptions of the project and research objectives, plans for research data collection, use and storage. The privacy of the children and the teachers was protected by ensuring that no identifying information was available to anyone who was not directly involved in the study.

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