3D Printing as Learning Activity in Higher Education

A case study in a robotics' prototyping course

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Abstract

This thesis is inspired by the new opportunities new technologies provide in education and more precisely in higher education. There is a general focus in higher education on supporting student learning beyond learning the existing knowledge, so that students are prepared for taking part in knowledge- generating activities in their future working environment. Technologies can offer new opportunities for exploring and constructing knowledge. The focus of this study is on 3D printing as a learning activity, which is interesting because it denotes both the use of new technology and a process which embodies design activities. Although there has been some research related to the use of 3D printing in educational contexts. There are really few studies focused on learning with 3D printing and the already existing ones, have typically focused on one aspect of the printing activity, rather than the design and printing process as a whole. To get a deeper understanding on the different aspects of knowledge construction and exploration with the use of 3D printing, among higher education students, this thesis was framed with the following research problem:

The problem addressed in the thesis is how 3D printing may support learning and knowledge construction in higher education and how this activity relates to students' learning experience. To tackle this, the thesis aims at answering two research questions:

1) How does 3D printing as a tool and a process provide students with opportunities for exploration and knowledge construction during a robotics' prototyping course in a university setting?
2) How do the teacher and the students perceive the usefulness of the 3D printing for learning purposes and what challenges do they face?

As this study focuses on knowledge construction in technological environments, analytical perspectives were needed that could examine how people construct this knowledge through the use of tools and artifacts. Given this prerequisite, a socio-material perspective on knowledge practices and learning was employed as a theoretical frame. This perspective combines insights from socio-cultural learning theories on the situated and emergent nature of learning with cultural tools, with notions of knowledge-generating practices and of knowledge as inscribed in materiality. Theoretical concepts within this frame like these of knowledge practices, assemblages and mediated activities by artifacts/tools are further explored and applied in the data analysis in order to explore the research problem.

Given that the present work aims to study knowledge exploration and the perceptions of the students, this study uses a qualitative research approach. The qualitative choice allows for further communication with the students, providing a deeper insight into their experience of the learning environment. A case study in a specific course in robotics' prototyping was chosen to provide the ability to follow the design process over some time and to obtain in-depth information about the students' experiences of the activity. The research took place in a university in Norway. The data was collected from February until May of 2016. The main participants included eight students and the professor of the course. The data material consists of two parts; participant observations and semi-structured interviews with students and the professor. The data material was subjected to a thematic analysis in order to answer the two research questions. To facilitate the understanding of how the design process and 3D printing activity evolved over time, two indicative design processes from the students' work were selected for presentation in the thesis.

The findings show how students take part in a range of knowledge practices during the 3D printing process, such as designing, visualizing, testing out, assembling, redesigning and printing. Through these practices students are involved in knowledge construction and exploration. The whole process is iterative, in other words it goes back and forth between the different practices of designing, printing, testing out, assembling, redesigning. The analysis also shows how the printing activity allows the students to assemble and work on different knowledge forms and representations. An important feature of the 3D printing was how it allows for tactile learning, in the sense of engaging with and learning about different materials and how these can be used in the design process. 3D printing is considered as useful by the students to learn the content and the processes of the given course, but also in work and leisure contexts. Nevertheless, when it comes to usefulness, students emphasize more in features related to their learning process, such as free expression, creativity, bringing ideas out to the material world, motivation, learning technical aspects and how to fix malfunctions or thinking in different ways than usually.

Technological affordances also play an important role in the knowledge construction. Such affordances include the technological ones, like the possibility to choose between different materials, the rapidity of the production offered by the printer, the various possibilities of the CAD programs, the precision of the printers or the technical problems that might appear during the printing process. Hence, challenges in learning with 3D printers include the challenge of knowing what the different technologies and artifacts can offer in the process.

This study provides a valuable stepping stone for similar research projects in the future. Given the positive experience of the participants in the study, it would be interesting to see further research where 3D printing is used in other fields of higher education, maybe even in social sciences, and explore how and if learning is facilitated in these contexts.

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1 Introduction

We live in a world surrounded highly of materials and technological which interact with human beings in complex ways. These technological apparatuses have reached such an evolution that it is possible nowadays to print actual material. This fact initiates a learning world with many possibilities and there is a fascinating perspective on imagining 3D printers in a classroom providing so many different possibilities. But then, one has to prove first that these possibilities exist. "*Facts are stubborn, but statistics are more pliable*" is a quote often attributed to Mark Twain, which can be interpreted as the power of written proof over facts. In other words, 3D printing may have many different pedagogical possibilities, but not much has been researched or proven, a fact that leads to the need to explore the research problem of this thesis.

1.1 The research problem

Nowadays technology is an important part of the student life in all the different disciplines and usually a requirement. Students have to be adaptive, fast learners; technology requires from them that they do not only wait to acquire knowledge within the limits of the university campus, but beyond that, that they learn how to search for the knowledge themselves. Jonassen and Land elaborate the same argument when they suggest that the theories in learning are changing and in comparison with the previous behaviorist ones, the modern theories require from the students to be active learners, as learning consists of a constructive procedure (Jonassen and Land, 2012). Higher education has moved beyond the learning of given knowledge to involve the students actively in knowledge construction. Design and production of products is also important in this active learning and new technologies are supportive in this kind of processes as they offer new opportunities for knowledge representation and for exploring knowledge in multiple ways. In other words, the modern university and thus the labor world require from the students to construct their own knowledge: and technology is an arguably important factor that led to this. 3D printing as a new yet fast changing technology that is related to knowledge construction in the field of higher education. By focusing on 3D printing, this study may shed light on this kind of new opportunities for learning with technology in activities that involve design processes and knowledge construction.

As it is, there is a need to discover how 3D printing facilitates knowledge construction and how learning through it, is perceived by students and teachers in higher education. Furthermore, it is important to have in mind that 3D printers are to be approached not just as simple objects, but as apparatuses with embedded theoretical knowledge in the whole process of producing material artifacts. This is to say that 3D printing includes the whole process of creating an object and not just the product itself.

Despite the fact that 3D printing is a developing technology with encouraging effects on learning so far, the research on this issue is hardly sufficient to strongly support the connection between the two and especially in the higher education field. Hence, this study is important for three reasons; first it will contribute in informing the concerned actors in higher education on the value of the 3D printing in knowledge construction and secondly it will offer a background, context and research material for further investigation of the issue. It will also provide recommendations for future exploration. Technology is part of everyday life and 3D printing is a very interesting technological tool with continuously expandable possibilities which we might soon consider using in the classrooms more regularly and efficiently. For this to happen the relevant research should be done and be available.

Maps showing topography and demographic elements, replacement of modified mechanical parts, printed molecules, cross sections of organs, 3D artwork versions, prototypes of engineering models, architectural models or historic artifacts are only some of the possible creations that a 3D printer is eligible to produce in the context of higher education (http://www.teachthought.com, 25/02/2016). Consequently, one would argue that 3D printing can be used in many and diverse disciplines. Nowadays 3D printers are being used in many higher education institutions, but mostly by the STEM disciplines. The few researchers that have been doing research on the effects of 3D printing on learning, for instance Kostakis et al. (2015), McGahern et al. (2015), Rodenbough (2015) or Horvath (2014) have proven 3D printing to be quite encouraging and stimulating for learning. 3D printers actually trigger students to learn design skills in all STEM, art and history fields through visualization (Horvath, 2014). Although the research that has been realized in the field is relatively restrained and focused on the mostly positive results until now, it is arguably important to elaborate further on how and if 3D printing can facilitate knowledge exploration. For the educational and learning possibilities yet to be researched, 3D printing has created a ‘niche’ in the world of socio-material learning, calling for exploration.

The research problem that is explored in this thesis concerning apparatuses such as 3D printers, when approached in educational contexts, is how 3D printing may support learning and knowledge construction in higher education and how this activity relates to students’ learning experience.

In order to investigate this problem, the thesis aims to answer two research questions.

1) How does 3D printing as a tool and a process provide students with opportunities for exploration and knowledge construction during a robotics' prototyping course in a university setting?

This question concerns how students become engaged in knowledge construction during the 3D printing process and the special demands that 3D printing presents to students as learners. It will be addressed by examining how different knowledge is assembled in the activities to support learning, how the students engage with it in explorative efforts, how knowledge and practice are mediated through different tools and representational forms in this activity.

2) How do the teacher and the students perceive the usefulness of the 3D printing for learning purposes and what challenges do they face?

This question seeks to explore in what way students' learning is perceived by both the teacher and the students themselves, through the use of 3D printing. Furthermore, it aims to explore how possible challenges are tackled in the learning context and if these challenges are connected to knowledge construction. In addition to focusing on the students' experiences the professor's ideas provide another point of view to the research. The interest concerning the professor, is focused on how the tasks are organized by him as a teacher, and thus what are his pedagogical intentions as an integral part of the learning activities.

1.2 Concepts- Definitions

In this section, the aim is to give a definition-description of what 3D printing is and how it works, so that any reader can get an idea of what are the possibilities and the different practices included in a 3D printing process later on. A combination of different definitions is presented, where important parts of each, come together to provide the reader with a depiction of what is 3D printing, so that he/she can get a better understanding of the present study.

1.2.1 3D printing- Rapid Prototyping

In ASTM (2010) 3D printing is defined as the additive manufacturing of a three-dimensional object and refers to the process of cross section layering (starting horizontally). More specifically, material is added on top of each layer so that the object will be constructed, acquiring the adequate information from a scan of the original object, or most usually by computer-aided design software, like CAD (ASTM, 2010). Materials might be liquid, powder or another sheet material (Gibson et al., 2010). Notably, a 3D printer can construct an immense variety of objects, from engineering steel parts to titanium implants and plastic objects (Encyclopedia Britannica, 2015).

One has to have in mind that 3D printing in this study will be approached as a tool and process that stimulates the construction of knowledge. As such the 3D printing is not just a printing method, but a complex process which includes the use of software, the use of hardware and the acquisition of previous knowledge to reassure that both will function properly. It encompasses also designing, printing and assembling a product.

1.3 Research Design and Analytical Perspective

To respond to the research questions of this study, a socio-material perspective on knowledge and learning is employed. This perspective is used in the context of a case study in one course, in which data has been collected, both on the design process and the experiences of the students and the professor, through a qualitative methodological approach which will be further described on the methods chapter.

It is considered important to argue on the use of a socio-material approach. There is a whole material world around us. Objects we use, objects we create, objects we manipulate and materials we explore. Objects are a major part of everyday life, from the simplest to the most complicated ones, such as technological apparatuses. One should note that objects do not just exist. There is a meaning in every object that transcends its immediate functionality. In order to further explain this, Fenwick and Edwards (2011) quote Vygotsky and Piaget who were strongly suggesting that possibilities for learning are created through interaction with objects. That is to say that people learn while they move as active entities in a material world.

According to the socio-material theories, learning can take place in many different ways through the objects around us; through manipulation, through creation or through use. Learning is not only taking place, by merely reproducing theory, but via the material world, which actually embodies knowledge. Materiality in learning can be found in different fields such as higher education or organizational learning and practice, where research is trying to bring into usable condition materials in social life and redefine their educational substance (Fenwick and Edwards, 2011).

Technologies are currently a big part of this socio-material world, by offering a big variety of apparatuses and software which can be approached as learning resources. Säljö claims that technology becomes important for an internal rearrangement of how our skills are being developed and how intelligence is being expressed; through the influence that technology has on our cultural context and our cognitive enactments (Säljö, 2010). One of these technological apparatuses, which is relatively new and combine both theories on materials, creation and use of objects, is the 3D printer and as Horvath (2014) says there is a magical and futuristic element in watching a printer creating a material object from a zero-point.

For the purposes of this thesis, a master course on robotics' prototyping from the Informatics Department of a Norwegian university was chosen. It is currently the only course at this university where students regularly work with 3D printers. The organization of the course around assignments that involved 3D printing in design activities made it productive for examining the research questions. Eight students and the professor of the course participated in the study. The data was collected by participant observations and semi-structured interviews with the students and the professor, as well as collecting images of the design products in various phases.

1.4 Thesis outline

Chapter 1 is the introduction chapter that includes the research rationale and problem as well as the research questions and a short introduction to the background.

Chapter 2 is a summarized overview of prior research related to 3D printing applied in learning environments and evaluates the main research outcomes. Relevant studies are presented showing how 3D printing has worked for learning purposes not only in higher education contexts.

Chapter 3 describes the theoretical perspective of the thesis. There is an emphasis on the socio-material theoretical background to explain how people construct knowledge. Furthermore, there is an elaboration of the concepts used to support the data analysis and presentation.

Chapter 4 provides the reader with an explanation of the methodology that has been used in the present research, namely the research method and the data collection and analysis tools, justifying also the choices made.

Chapter 5 consists of a presentation of the data provided by the research, starting with the participant observation process, followed by a presentation of the interview data in themes such as knowledge practices, materiality, technological affordances and pedagogical challenges.

Chapter 6 provides a discussion of the results of this study in parallel with the theoretical framework. This discussion is based on both the collected data and the theory in a way that answers back to the research questions. At the same time, it is an explanation of how certain theoretical tools support this specific study.

Chapter 7 is a brief conclusion of the research results and limitations of the study and includes suggestions for the future research. Here, also the importance of the study and how it differs from previous research is explained.

2 Literature review on the use of 3D printing in Education

As it is mentioned, 3D printing is a relatively new technology. Thus, there is not much research done in how the 3D printing can be used as a learning tool. Furthermore, the big majority of the research conducted on this subject is quite specialized in the learning of one specific subject, for instance the kanji writing (Kanev, Oido et al. 2012), rather than in learning as a process. However, as Tight (2012) claims, there are differences concerning learning of different groups of students, but there are also common patterns. As such, the literature review will be based in different ways in which 3D printing is being used as a learning resource in various knowledge fields.

The majority of the existing studies is focused on some kind of scientific field and not on learning. Given that learning is an important point of our study there will be an overview of the most important and relevant points of these studies, although they are not immediately attached to the higher education context.

First there is a study by Kostakis et al. (2015), who researched the effects of 3D printing on learning in the high school context in Greece. More specifically with the participation of a total of 33 students, from one private and one public high school, Kostakis et al. in this article are trying to find out to what extend the technological width of a 3D printer can offer a fruitful ground for learning or for a way of communication between the students who are blind and the ones who are not. The students used an open source 3D printer to make functional objects that they chose with the condition that all objects should have on them printed messages in Braille language because they would be given to blind students (Kostakis et al., 2015). The results were quite interesting: 3D printing provides the learners with a different way of thinking and seeing the world, it stimulates several literacies and creativity, it inspires engagement in projects, it makes students choose what they want or need to learn and it makes it really easy to materialize your ideas and share them in class (Kostakis et al., 2015). Kostakis et al. (2015) also refer to the high cost of the printing and the limited number of 3D printers in the institutions, but as they claim, the costs are declining continuously. Finally, they report some classroom functionality issues that they confronted successfully, such as the different ICT skill level of each student and the challenging advisement provided to the students, due to the complexity of the produced objects (Kostakis et al., 2015).

Another interesting study centered on learning and especially on mental rotation is that of Chen et al. in a primary school context. Chen et al. (2014) realized a research on how 3D printing can aid the mental rotation ability in 46 primary school children at the age of 10, as this is an age with increasing development of the rotation ability. They tested the mental rotation ability of an experimental and a control group before and after the seven-month course, with results showing no considerable difference between the two before the course. The experimental group had information of Google "Sketch up" on how to design 3D printing models and practical information on the 3D printing process while the control group had conventional classes. The results are particularly interesting; the 3D printing courses aided noticeably the mental rotation ability of the boys (Chen et al., 2014).

2.1 The Science fields. Medicine, Biology, Chemistry

Maybe the most extended use of 3D printing in higher education happens in the medicinal field in many cases. Studies show that it is cheaper and faster for prototyping while it provides students with a better understanding of shapes and processes.

However, not in all studies in this field, are students involved in the 3D printing process. As such Vaccarezza and Papa (2014) conceived 3D printing in anatomy from a different point of view and presented the value of 3D printing in constructing models or implants in the anatomy education. That is because it provides very low-cost models for teaching that can provide a solution for the deficiency of human bodies and governing or moral problems concerning the cadavers (Vacarezza and Papa, 2014). After elaborating the importance of the physical model for the human and veterinary anatomy students, Van Epps et al. (2015) they also support the 3D printing as a cheap method to print bone kits for the students in human anatomy education. The 3D printing in human anatomy classes, they say, emphasizes on the reception of a stimulated –through objects- communication via learning. Augusto et al. (2016) also perceive 3D printing as a didactic tool in Biology, but in this case, for the representation of blood cells. They are trying to tackle a very specific problem; young people, they say, are no longer interested in science and technology and one basic reason, amongst others, is that there is neither technological evolution nor teaching strategies for science, especially in developing countries. For that the suggested solution is technology in the context of "Learning with Technology" through simulations and online tools (Augusto et al. 2016). They also mention that the current material in cell biology is not that realistic making the field unattractive. For Augusto et al. (2016), the 3D printing is a valuable tool for introducing real-like models instead of flat images and thus aiding the comprehension of the morphology and the functions of the cells. Another advantage of the 3D printed cells is also that they can be used by blind people (Augusto et al. 2016). They developed 3D models for six different types of blood cells using three different approaches. Nevertheless, they do mention that when it comes to how this process relates to students' learning, the topic is still under investigation.

For that investigation, there is a relevant research where McGahern at al. (2015) opt for producing replicas in Biology class with 3D printing, as the process stimulates the engagement of the students, offering a new and alternative way of approaching the biology class processes and a deeper knowledge on the objects they are willing to make. McGahern et al. (2015) present the case of a student that used 3D printing for the undergraduate biology seminar and actually showed them how to use the 3D printing for students learning. The student in question wanted to create a root-tip cross section and for that she first considered clay, but the result wouldn't be professional, she had not the indispensable tools in her disposal and there would be no color variety. In the end, the college decided to give her permission for the use of the 3D printer which was still under development in the pedagogical context. As they describe, in a time-period of several weeks, the student used free software and had to focus to several details such as morphology, dimensions or cellular properties in order to create a very precise model of extremely low cost. In contrast, other students as McGahern at al. (2015) mention, invested very little time on the project because they were restricted in creative means so they justified it by claiming that the result would not look better even if they spent more time.

The student that realized her project by using the 3D printer expressed her opinion on the procedure, one of special interest:

> *"I feel using the 3D printer to design and create a project allowed me to learn a lot more about the subject than I otherwise would have. However, the most valuable part of this project was the skill set I gained in learning how to operate 3D software and upload and print these designs. Knowing how to use a 3D printer as an undergraduate student gives me an edge and a skill that sets me apart from other students and makes me more marketable in the modern employment market."*

From that point, the professors started to rethink the educational value of 3D printing and use it in class. However, McGahern et al. (2015) do refer to some limitation of the 3D printing in class such as the long-time span required, the over specialized knowledge for the use of the 3D printing software (depending on the product-aim) and in some cases the difficulties in refining the product due to the layering or the limited resolution.

Many applications are also suggested for Chemistry classes; a couple of them are presented here by Smiar and Mendez (2016) and Dean et al. (2016). Smiar and Mendez (2016) propose an educational approach with 3D printed models to aid the understanding of the Bohr model of the atom, the bond polarity and the hybridization. They used low cost equipment and open software to make models that cannot be fully represented in two-dimensional pictures. An interesting part of this article is that students were also asked to make their own atoms and then recognize the atoms of other students. However, there are no details of the process. What Smiar and Mendez (2016 do) mention is that most students stated that they had a better understanding of the different concepts after the course and the high percentage of students claims that the 3D artifacts helped them. Another application of 3D printing in chemistry this time in an even more relevant higher education context is proposed by Dean et al. (2016). This time the authors also mention the importance of perceiving the three-dimensional objects in chemistry as they are and they worked especially with the VSEPR theory[1]. For this research context, undergraduate chemistry students were given 3D pens[2] and two-dimensional templates in order to make 3D ABS models. The students of the experiment were given certain templates to step on so they would not need any special artistic skills and the shapes that were created were meant to be like puzzle pieces so that the students would combine them into molecular VSERP shapes (Dean et al., 2016). The results of the research were quite controversial; from the one side the process required too much time for the students to draw well, which means that it is more laboratory material, there were safety issues concerning the 240 C^o at the edge of the pen and problems with the mechanical features of the creations that are not robust. On the other side, they say that *"in the correct setting, hand-held 3D printing pens are a potentially powerful tool for the teaching of VSEPR theory"* (Dean et al., 2016: 1660) and that a 3D pen can be an alternative, fun and cheap way in learning molecular geometries.

2.2 Technology, engineering and Design

Throughout the literature 3D printing is being used a lot as well in fields such as engineering and design. Modeling and prototyping are the most common purposes that 3D printing covers in these classes.

According to Horvath (2014), 3D printers shall serve various purposes in a classroom, from designing, engineering and art to history, biology and mathematics. Horvath in the book "Mastering 3D printing" provides a chapter with examples from several experiments, where 3D printers were used in class, along with possible applications, reactions of the students and restrictions of the

[1] Valence shell electron pair repulsion

[2] The researchers explain that the hand-held 3D pen is a new invention that extrudes melted plastic in at a point in a space that is given by the user and one can either make 2D sections and combine them together to a 3D model, or draw in 3D from the beginning, which is quite unusual (Dean et al., 2016).

process. Her suggestions concerning biology were presented before. On engineering Horvarth (2014) presents a problem that came up in the Windward school in LA, where students were called to create drain covers that wouldn't brake by the lawn equipment and thus solve a practical problem of the school. In this way, she shows an example of how 3D printing can inspire the elaboration of design skills. The interesting part, she mentions, was to follow the students who started from the defected original drain cover and see how they elaborated different ideas in the process that were simpler and easier to be printed. She underlines that even such a small project, in order to lead to some new creation, required the understanding of many features of the process. Another interesting point form Hovarth (2014) is that while working on the project, students that understood better the 3D printing started helping others creating an environment that stimulated the team work. 3D printing, she suggests, is an open tool for fine arts as well, as it allows for "experimentation and prototyping", although for some arts using a software might seem inappropriate or it might create overestimated impressions about the limits a 3D printer can have (Hovarth, 2014).

Further in more complex aspects of engineering, Ehud and Dror (2011) used 3D printing to enhance learning in an aerospace engineering class, to create wind-tunnel models. Their paper discusses how rapid prototyping of wind tunnels for testing can profit engineering students as a part of the fourth-year projects in the curriculum as well as different approaches to confront difficulties related to 3D printing. The exact production was two-aircraft models made by polymer-based rapid prototyping with some metallic details that were added afterwards. The prototypes were tested in a subsonic wind tunnel and the results of the research were approach in comparison with analytic predictions (Ehud and Dror, 2011). In their article, they also make a catalog of the advantages and disadvantages of the 3D printing process as far as mechanical aspects are concerned. They mention as a significant advantage, the facilities offered by 3D printing when it comes to complex geometry with internal passages and holes especially in contrast with the regular machining (Ehud and Dror, 2011). In their results, they also mention the lower cost and the possibility to acquire a model right away from the printer. Van Epps et al. (2015) refer also to the importance of 3D printing for the industry field and engineering because of the low cost and the variety of materials it can offer.

When it comes to the printing in the context of the academic activities, Ehud and Dror (2011) state that due to the timetable of the student's project, the CAD designing left little time for the wind tunnel testing before, but with the rapid prototyping the process becomes immediate, facilitating the procedure. Along with functionality within limited financial resources, these are the two features that highlight the usefulness of 3D printing for Ehud and Dror. On learning they mention that 3D printing gives the opportunity of testing the models in the wind tunnel, which provides the students with "*invaluable experience and taught them how to empirically validate analytical models and how to incorporate aerodynamic testing in their design process.*" (Ehud and Dror, 2011: 399). Furthermore, students came to face problems that had to do with mechanical aspects such as the *"product architecture, strength and deflection, manufacturing tolerances and assembly methods."* (Ehud and Dror, 2011: 400). The overall results by Ehud and Dror (2011) show that the rapid prototyping provide students with a way of learning enhanced and realistic.

2.3 Humanities: Language ad History

An article by Van Epps, Davin Huston, John Sherrill, Ann Alvar and Anna Bowen (2015) presents several examples of 3D printers being used in a higher education environment. They also comment on how the knowledge of using a 3D printer increases employability and how the presence and accessibility of 3D printing in university campuses has been lot bolder the last ten years. They make suggestions for the use of 3D printers further from engineering prototyping and anatomy, in English language courses or just for creativity purposes ("the fun side"). First, they elaborate the example of an English class in the Purdue University, where 3D printing was used to support the learning of digital rhetoric; students were asked to use digital media, in this case 3D printing, to create interactive objects from the daily live that would provoke the engagement of people to technological, social or cultural matters. There are two examples given by Van Epps et al. (2015) from the results of this course; a phone case that questions the relationship of people with their phones and a PEZ dispenser with the head of the Purdue University's Pete sports mascot, which was voted as the creepiest one. Last but not least, they mention the fun side of 3D printing that offers the "joy of creation" to both students and staff, through discovering and creating "your own" things, which lead them to the suggestion of 3D printing being available to all, through the libraries. Concluding, they state that 3D printing embeds the development of new skills and technologies and an alternative view of materials which in any other case would be of no interest (Van Epps et al., 2015). Concerning the English class, they say, 3D printing embraces the learning of new skills in design and construction of objects for stimulated communication. They also underline the importance of 3D printing for libraries, as it would promote their importance for advancing learning both for students and faculty.

Kanev et Al. (2012) contributed in the field by researching how printing three-dimensional kanji ideograms can function as a resource for learning the kanji writing. For them learning the Japanese kanji ideograms is a complicated process for middle and high school students and they attempt to show how 3D printing can aid this process in the early stages. They emphasize the importance of perceiving the kanji ideograms as pictures that depicts the real world. Hence, being able to see and feel these “pictograms” in three dimensions is a considerable step in learning and understanding those (Kanev et al., 2012). Kanev et al. (2012) use the 3D printing to create Kanji construction games in order to provide an alternative way of learning the Kanji ideograms. In their conclusions, they report that the three-dimensional printing embodies new palpable and other associations, which may have positive effects on the learner’s understanding and memorizing skills. Furthermore, they state their engagement in researching further new ways to extend the design and construction of 3D printed kanji ideograms.

In the history domain, Hovarth (2014) collaborated with the MIT museum to prove that the 3D construction of historical objects could easily be done by students and can offer a valuable visualization of these. Through this process one should learn about the construction means of the specific era he is focusing on, leading to deeper thoughts on the design process and thus it would also create possibilities of coordinative work between engineering and history students (Hovarth, 2014).

2.4 After School Activities

Another interesting part of Hovarth’s (2014) work refers to after-school activities with 3D printing. One of these activities is the construction of robotic particles with 3D printer which according to her, leads to exploration of how strong some parts should be, if the design is the appropriate one and when it is completed. Another one is a program called DIY girls where 3D printing is used in a low-income community of Los Angeles to teach to girls of the 5^{th} until the 8^{th} grade technical skills that are not conventionally taught to girls; “soldering 3D printing, programming or building electronics”. Adult women can also apply to the program (Hovarth, 2014). In the end Hovarth (2014) suggest that by learning 3D printing people can gain valuable experiences and knowledge about 3D printing as the interest in prototyping from the industries is increasing and it is somehow an introduction to more complex machine tools if someone wishes to follow such a career.

2.5 Summary

The literature review showed that 3D printing has been a useful learning tool in different fields and disciplines. Although there are various cost or time concerns, the teachers overcome these according to the research, showing that the 3D printer can be an arguably important learning tool. The overall educational experience from the use of 3D printing is positive in all the different educational levels with advantages coming from the immediate results 3D printing can provide, the tactile experience that students can have with their creations and the process of detailed designing. The literature review shows a new tool with many possibilities yet to come and very few concerns on possible burdens. However, one should consider the technology-optimism of the authors. Arguably 3D printing has much to offer, but as it is a new technology it is possible that many problems maybe have not emerged yet. Furthermore, people who are both designers and writers on 3D printing might be biased in a certain way. In any case all the literature presented here is considered important for this study, as the results analyzed are relevant to the use of 3D printing in educational contexts.

What is still missing from the presented literature is research on how 3D printing is used for learning in different knowledge domains in higher education. Moreover, we need a better insight in how different knowledge forms and materials are used in knowledge construction, and in how the design process interplay with tactile experiences and materiality in this activity. Whilst a majority of the existing studies use perspectives from constructivism to support their findings and arguments, the role of materiality is not sufficiently accounted for, although there are nuances in the findings. The present study contributes to this gap by employing a socio-material perspective in the analysis of 3D printing in a specific higher education context. Moreover, by examining the different practices and phases in the process rather than focusing on a part of this process or on the printed product only, it aims to provide better insight in 3D printing as a *learning* activity.

3 A socio-material perspective on learning and knowledge construction

3.1 Introduction to the chapter

This chapter presents the theoretical frame which guides throughout this study. Here, there will be an introduction to the main theoretical assumption that will be used to construct this frame. The research questions of this thesis ask for conceptualization of given processes; these conceptualizations shall include how knowledge can be constructed and explored via artifacts and specifically via 3D printing, as well as possible ways of 3D printing being perceived as a useful technology for learning. Starting from setting the basis with socio-material perspective and knowledge creation, there is also a focus on several concepts that follow up; some of them such as have a hermeneutic function for the application of the theory on the phenomenon. Others such as these of meditation and representation are being used to show how learning is related to the 3D printing and to explain the choices made for the data collection methods. In the beginning, there is a focus on the learning world, then it will move to how learning is happening throughout tools and further than that, to the role of artifacts.

One thing that is important on the understanding of this conceptual framework is that 3D printing is one process which entails different steps and procedures from designing to the production of an object. Thus, in order to explain how learning could happen through 3D printing multiple theoretical tools shall be engaged.

3.2 The main assumptions of a socio-material approach

Sociocultural theories will be used with a focus on materiality when needed, to provide our main conceptual tools. In order to proceed further with the theoretical perspectives that will be used as fundaments for this research, it is considered important to have a more holistic view of what the socio-material perspective implies.

To get a better insight into the socio-material perspective and in relevance with this study it might be valuable to have an overview on how socio-materialists perceive learning. It is this very learning that the researcher seeks to find out how it is facilitated by the use of 3D printing: The socio-material perspective then, *'assists us in providing interpretive explanations of learning practices that account for technology contextually'* (Johri, 2011: 215) and can be applied to every kind of learning as they all happen through materiality (Johri, 2011). Papert based on constructionism provides a further understanding of the context claiming that *'students learn better when they are in charge of their own learning'* (Papert, 1993; Ackermann, 2001) For this same learning, Bruner says, that it is dependent from our culture and devices and that the creation of knowledge is actually resulting from the cultural creation, communication, tool-use and invention (Bruner, 1977). Learning happens in a social context by interfering tools, also for Säljö (Säljö, 1998). He describes how the knowledge someone acquires is the function of the mediating tools he has been using. All these researchers approach learning as a process of knowledge construction that happens within one's self and is embedded in our culture and all that this culture might include: devices, communication, tools. This overview of the essential ideas in the socio-material perspective is considered important in order to get a further understanding of the specific theoretical perspective and concepts that will be elaborated for the purposes of this research.

Although for some fields of educational literature, the socio-material perspective seems to be recently in focus for research, it has been further connected with fields like higher education or workplace learning (Fenwick and Edwards, 2013). In order to tackle the research questions presented in this paper, one would take into consideration how the socio-material perspective is important and different to any other constructivist theories; The previous literature on how technology relates to learning seems inefficient at covering all the aspects of socio-materiality and leaves open problematics, such as the equality of social and material aspects or the dualism of socio-materiality (Johri, 2011). Finally, Orlikowski and Scott (2008), propose an approach by focusing on agencies. Agencies are used here, to interpret the socio-material perspective in a relevant way for this study. They actually show how the socio-material perspective, in contrast to other learning theories, focuses on how all learning practices have a priori both material and social nature. According to the two researchers the problem is to be solved by a theoretical compilation of the social and the material, while taking under consideration their separate natures (Orlikowski and Scott, 2008). For Johri (2011), the aim in the socio-materiality, based on the ideas of Orlikowski and Scott, is to show how the objects/materials overcome their meaning to become learning resources. Johri (2011) underlines that the dependence or independence between the social and the material is of no importance; what matters is that all social, technological, human and material elements are attached to each other.

In this way, the socio-material perspective provides theoretical lenses to look at technologies in learning without emphasizing only to their social or material entities, but to both according to the needs of each study. On this, Johri (2011), explains that the socio-material theory is very important in order to surpass the dualism that is attributed to the learning technologies in the existing literature, which draws a clear limiting line between the social inferences of using the technologies and the material features of design in technologies. This separated perspective only benefits one aspect, either the social, or the material (Johri, 2011). As such, Johri and other researchers also argue that in order to show the coherence between learning and ICT there is a need to allow for *the shifts in assemblages by leveraging different affordances[3] of the material and even of the social* (Johri, 2011; Hutchins 1999; Pea 1993a; Norman 1991).

'Practice theories' seem to follow the same logic as well, according to Markauskaite and Goodyear (2017: 199) who suggest that these theories perceive the human mind as an actor dynamically interacting with not only the social reality but also the material, the semiotic, the individual, the collective, the psychological and the cultural emphasizing in the equal embroilment of both the human and the material that is being expressed in practice. The double social and material nature is indeed one essential characteristic of 3D printers as by definition they combine both elements

3.3 The knowledge creation metaphor for learning

This study is about how the activities included in a 3D printing process can facilitate learning. For this purpose, the model of knowledge creation by Paavola et al. (2004) will be used. Paavola et al. (20004) present three metaphors for learning relying on different learning perspectives in order to show in which ways these models are similar and how through these there is a new emerging metaphor focused on knowledge creation through mediated procedures. The knowledge creation is the newest metaphor and the most relevant one for this study. It does incorporate though ideas from the former ones. This leads to a better understanding of what roles materiality may take in learning processes. As they show, the learning metaphors have joint points where they complement each other in order to provide a certain way for understanding learning (Paavola et al., 2004). This concerns the knowledge creation model which explains learning in two ways: First of all, learning means that there is something new which emerges and which is being elaborated. But more

[3] Affordances: Different social and material aspects of the assemblages. In other words, affordances are what the materials/artifacts bring with them as opportunities or constraints for how they can be used, what types of learning or work they can allow for…. The inscribed opportunities and hindrances that come with the artifact 'itself'.

importantly, learning can also be interpreted as a process that takes place within collective objects in practice (Paavola et al., 2004). This means that learning is a shared development where people try to unfold artifacts like "*knowledge ideas, practices, and material or conceptual artifacts*". The connection of these artifacts leads to knowledge construction (Paavola et al., 2004: 569). For the purposes of interpreting how learning happens in this study one shall consider how through this knowledge creation metaphor, knowledge in not something just to be created but further than that, knowledge can be altered and molded. In this thesis, opening up the type of knowledge construction and exploration that happens in the 3D printing activity, one comes across different knowledge practices students engage; these can be designing, simulating, printing, testing out and assembling. These can be also perceived as design stages as presented by Maier et al. (2014) and analyzed further in 3.6.

What is following up in this chapter is an introduction on how one can analyze different aspects of the learning process in this master thesis. First, there is a closer look on how artifacts facilitate knowledge construction and then a focus on the material objects as artifacts. In other words, how knowledge creation happens with the artifacts as cultural tools and processes. Artifacts can be perceived both as tools and processes and for this study both will be needed as 3D printing starts being an object exactly at the point where it stops being a process. In some ways, these two functions emerge simultaneously as the object in function leads to different processes. The basic assumption in this study on how learning is being perceived is that we as people interact with artifacts all around us, such as the printed objects of a 3D printer, and throughout this interaction – even if it is not a tactile one- we get to process and combine different information and learn, in other words, to build knowledge. To use one primary concept of this research, one would say that artifacts mediate knowledge construction in the socio-material world.

3.4 The mediating role of artifacts

Artifacts/tools can be found everywhere around us in our daily lives. Vygotsky had as a central idea the perception that the use of cultural artifacts for learning, differentiate us from other biological species (Säljö, 2010). Artifacts can be objects, services and means of communication that within other functions that they can achieve, they can also stimulate the production of knowledge. A 3D printer is a machine that produces artifacts. Hence, socio-material and constructivist ideas are eligible to offer a well-founded background to investigate how the 3D printing can actually facilitate learning. Learning was already interpreted earlier within the socio-material context as a mediated process throughout the knowledge creation metaphor.

First of all, the socio-material perspective explains how knowledge is embedded in the material world which in turn is a part of our social culture. Furthermore, the socio-material perspective can connect the artifacts and tools that are a central part of this hermeneutic frame, to learning in a social context. Tools differ from the artifacts in a way that tools represent a functional concept. As Vygotsky (1997) describes intrinsically, a tool is used by someone to serve a specific activity of his and it shall result to a change or to some other object. In other words, something becomes a tool when it is used in an activity, in contrast with artifacts that are all human made things from material to semiotic. Tools and artifacts that exist everywhere around us owe their invention and survival through the generations, not to one creative mind, but to a big collective, to the society they found their use into. Säljö (2010) explains to that end that tools are not creations of one single person; on the contrary people managed to know and use them because of their use in the society in which they socialize. That is why usually the use of tools does not presuppose that people know how they reached the current era.

Having at this point an understanding of the sociocultural learning, Wartofsky (1973) will be used to investigate the different types of artifacts. Throughout the sociocultural literature one might encounter many times words such as objects, tools, artifacts or assemblages. For the following interpretation though, it would be most relevant to encounter 3D printing as an artifact fitting into Wartofsky's three-part distinction of artifacts. For Wartofsky (1973) there are three stratified types of artifacts: The primary artifacts that are being used to construct things, such as tools, the secondary artifacts that are embodiments of the primary ones and represent ways of acting using the primary artifacts and the tertiary artifacts that are creations of the imagination. For Wartofsky, the three kinds of artifacts play a considerable role in mediation. What is important is that Wartofsky's artifacts can be applied as a whole, to a hermeneutic context for 3D printing as an artifact, due to the fact that it can take all the three different roles, an approach that will be analyzed further in 3.6.

Another important concept that can be related to learning is that of language, that can be a secondary artifact. In most of the articles about mediation and tools in sociocultural context, one will always find quotes of Vygotsky on the importance of the language as a primary tool. Vygotsky (1978) supports the idea that language is the fundamental mechanism to mediate what occurs in the world and insists extensively on the connection that takes place between language and thinking. He emphasizes that language is important for individual and collective learning because it can be used at the same time as a tool for communication between people and as a medium for processing thinking (Vygotsky, 1978). In addition, with language Vygotsky introduces a link between the external environment, aka the interaction with other people, and the internal one, aka thinking. Säljö (2010: 500) goes further into the subject to demonstrate that language is more than a double tool; language is *a mechanism of semiotic mediation* which means that it provides us with thinking through signs. In the sign-mediated communication we get involved in the world through cultural tools each time we communicate or implement physical activities (Säljö, 2010: 500).

3.5 Knowledge forms and representations

After acquiring a further insight into the basic theoretical assumptions that guide this research, in other words socio-materiality, knowledge creation and the explanatory concept of artifacts, the key concepts and processes will be presented in this section. Two are the basic concepts that will guide the approach of the research towards 3D printing as learning resource as well as the methodological approach: This of mediation and this of representation. While the concept of bricolage can be used for a better understanding of the sociocultural learning context of 3D printing, the analysis of the data of this study will be based on these different analytical tools of mediation and representation.

When discussing the idea of artifacts, it was mentioned that the acquisition of knowledge can happen through artifacts. This “through” implies a mediation process which is one of the central concepts of this analytical framework. In a more general context one could suggest that all human actions are actually tool-mediated; mediated by all kinds of different material or non-material tools, such as the language and by a variety of resources. As such mediation is an internal characteristic of our social doings. In other words, the term of mediation refers to the interaction of the humans with their ambiance in an indirect way, in a way that they use different artifacts –result of the cultural and historical evolution- when they communicate with their surroundings and with others (Wertsch, 1991). In a few words, we exist in an interchangeable environment and this stimulates knowledge.

In a sociocultural perspective, it is important to recognize how one’s actions are being mediated through different cultural tools in order to explore learning and knowledge production. For Vygotsky (1978) tools differ from signs, while for Säljö (2005) on the other hand, the cultural tools have both material and intellectual aspects. What is hard for most of the researchers is to explain how the two types of tools are separated and to what point this separation starts. Cole (1996) exposes the problem on a very simple yet essential way; He gives the example of an abacus and a simple arithmetic calculator that both are physical objects while they entail intellectual tools like calculations or the use of numeric rules. For Säljö (2010), this ability of turning the intellectual tools into physical ones is a unique ability of the human nature. Connecting further the two ideas Daniels (2015: 37), argues that there is a flaw between the intellectual and the material which creates a complicated and multilayered argumentative relationship in the way people interact in the world they are situated in and this way shows how the mind is artifact-mediated. In the end, these fundamental statements come together to show that tools, artefacts as means that mediate, aka provide, knowledge and thus learning, can have a physical nature such as a pen or a 3D printer device but can also have a non-physical one, an intellectual, such as the language we use to communicate or the programming language/software which is used to virtually design the object's layers before printing it. Both however encompass the material and the intellectual aspects. These arguments may also imply the simple assumption that mediation is everywhere in the human environment as long as one uses tools situated in it or even interacts with them: Because this is the way the human mind functions. Similarly, Säljö (2010: 499) argues that the several cultural tools mingle into the human activity and change the way that people argue, reason, communicate and process all types of activities. In the socio-material context 3D printing is perceived as such a tool that provides knowledge through designing and construction.

Daniels (2015: 36) after looking intrinsically into Vygotsky's and Wertsch's work on mediation, he connects it to 'a development in which mediators serve as the means by which the individual act upon and is acted upon by social, cultural and historical factors'. Furthermore, there will be a need to take a closer look to both explicit and implicit mediation as Wertsch defined them in an attempt to analyze the different ways Vygotsky is using the concept of mediation. For Wertsch (2007) explicit mediation consists in the mediation that is triggered by external factors that might be signs, people or objects and happens purposely and consciously, while the term implicit refers to the internal mediation which usually takes place in an unconscious form.

Another analytical tool that is considered important for this study is that of representation. One of the definitions given by the dictionary of Cambridge for the verb represent is "to be a sign or symbol of something" (http://dictionary.cambridge.org, 19/11/2016). Having as a starting point this definition, an object can be a symbol: a symbol of the knowledge hidden in that object. This is to say that all objects can be seen as representations not only of their obvious semiotic nature but farther, as representations of their whole constructing procedure, the ideas behind their creation, the whole designing process, the motives of the making or the solution of the production problems. There is a whole world of knowledge production represented in every object and this is how representation from a term becomes a meaningful concept for interpreting the exploration of knowledge that occurs when the students use the 3D printing technology.

3.6 The 3D printer and the 3D printing as learning activity

This section is a link between 3D printing and the theoretical framework which will provide the reader with an elaborated explanation on why and how the different concepts are considered important in relation with knowledge creation through 3D printing.

At this point it would be fruitful to open a discussion on how 3D printing can be different from other modelling technologies concerning learning, based on its a priori dual nature of the social and the material. This discussion will provide the reader with a better understanding of the 3D printing procedure and will lighten its special characteristics and advantages. In the first place, modelling is the ‘language of the designer’ (Maier et al., 2014). This is to say that a model process indicates the way the designer is thinking and represents his choices. By modelling one can encompass many different designing processes; some of them are draft designs or thought models such as flowcharts or drawings while others end up to an actual functional model (Maier et al., 2014). 3D printing is a part of the latter category but its uniqueness lies on the fact that it encompasses both virtual modelling (CAD) and physical products (manufactured object). Students can imagine the world in the making, design it and have a tangible result of this initial imagination to be tested.

As such a 3D printer can serve all the purposes of all the different types of modeling as mentioned by Maier et al. (2014): capture ideas, get insights, complete a design of a product (here: the pre-drawing), elaborate this design, manage the design process or find out the consequences of the solution the design is aiming to. Furthermore, while simulating a model, as in 3D printing, the result-product becomes more and more visible and concrete. Simulation might be the handling of the characteristics of the result-product in order to make assumptions of its behavior or an interpretation of the initial idea on the designer’s mind (Maier et al., 2014). Arguably, a 3D printer can be a tool that includes many different design/modelling processes and even more it is a tool which requires the refinement of all the previous design processes that it encompasses in order to produce the final object. More specifically, to print something with a 3D printer, one shall start from an idea, put this idea into a draft design, insert the design with every little detailed parameter in the software for the layering to be exact, fix the possible errors, choose the materials by guessing their behavior on the object, print the object, have a tactile and immediate relationship with his product that provides with the opportunity of controlling all the designing hypothesis. 3D printing is most possibly the only tool that can actually offer all these different possibilities. Hence, a tool that offers a beneficial ground for observing how students process all these different levels of modelling-manufacturing and how they learn through these.

When discussing the ways 3D printing differs from other designing-modelling practices, it is mentioned that 3D printing comprises a variety of designing procedures, through which students can learn. This creates a linkage to the concept of mediation. Mediation is central concept of this study because the 3D printer is conceptualized as a tool and a process that mediates knowledge. In addition, the research questions focus on the allowances of knowledge exploration that 3D printing can offer: in simple words, what knowledge is made accessible and thus mediated while working with a 3D printer. Furthermore, 3D printing can be further linked to the concepts of implicit and explicit mediation. Respectively, while working with 3D printing there is the external object –the printer- but it would be further interesting if it is possible to find out to what point the knowledge creation happens in a conscious form of learning through the different data collection methods.

In a similar way, 3D printing is connected to Wartofsky's different types of artifacts. For Wartofsky the three types of artifacts play a distinctive role in mediation. Considering the case of 3D printing, it is interesting to see how knowledge can be mediated in all the three ways; the 3D printing can be a tool of creation as a primary artifact that constructs things, it can be conceived as a secondary artifact for the part that requires software modeling to represent the object-to-make, while it can also be a tertiary artifact that offers opportunities for imagining parts of the world in-the-making, and for experimenting with tools to explore and produce new materials. In other words, one has to use the 3D printer first as secondary artifact in order to model his object, then as a primary artifact in order to print-construct the object and as a tertiary artifact during the whole process and especially before the modelling to imagine and mentally recreate the desired result. What one might find exciting in this whole exploration is how one single process might be capable of mediating knowledge exploration in so many and diverse levels.

Language as another tool introduced by Vygotsky is relevant to this study, not only because it provides a further understanding of how mediation and artifacts can be explored. Language is considerably important because it is a whole part of the 3D printing process. Like every computer-based system, the 3D printing has its own language of symbols and letters that one has to know in order to use it. One of the aims of the course of the research amongst others is the "understanding of the basic principles of CAD, rapid prototyping and CNC, being able to use CAD, rapid prototyping and CNC in practice…, know how to build, operate and program a simplified CNC milling machine…" (Course blog, 23/11/2016). This means that the students need to know how to program the computational system and thus how to give the relevant mandates (program) to the machine in order to produce work. In other words, how to speak the language of the machine, in order to communicate with it. The fact that the 3D printer has its own language means a priori –if Vygotsky's elaboration is taken under consideration- that it mediates information. The different CAD softwares are exactly this tool-language, through which the students will have to put their thoughts into symbols, for the 3D printer to understand and implement the will of the user.

Further on, concerning the concept of representation, Cole and Derry (2005) interpret Donald Norman's (1991, 1993) ideas on representation in a very interesting way for this research; Norman focused on representation through what he called cognitive artifacts. For Norman (1991: 17), cognitive artifact is "an artificial device designed to maintain, display, or operate upon information in order to serve a representational function". Although he does not define the context of this representation, Cole and Derry (2005) based on his analysis provide us with a valuable contextualization of the term: Representation is a group of symbols that stands in for the real event and when this happens, the material world around us is not suitable for interpreting any more. Among other they add that the importance lies on understanding well the representation and thus avoid focusing on irrelevant points and that representation is significant because it provides us with information on things or events that are not present in time and space or even imaginary ones. The significance of this analysis is that it provides us with an aspect of the representation that usually it is just implied. This aspect is that representation gives us information that is not absent at the point that the representation takes place, information about facts of the past through the object of interest. This interpretation of the concept offers a considerably relevant frame for our study; the research questions seek to find out exactly this "invisible" knowledge that students might acquire, which is being represented in the 3D printed object.

For Markauskaite and Goodyear (2017: 200) knowledge does not exist just in the form of subjective arrangement but it has to be 'represented' in the material mode. Specifically, for the 3D printing, emphasis shall be given to how knowledge is being inscribed/ represented –in other words, displayed- in the object of production. 3D printing allows for visualization of ideas and interconnects the previously just theoretical knowledge to a material and tactile object. Hope (2006) states respectively, that representations are not only about the product but mostly about the procedure of construction of the object. She argues further that when something is being visualized then its construction process becomes invisible (Hope, 2006). In a similar way, when someone creates a 3Dprinted object, there is a lot more in its printing procedure than the object itself: The object represents its printing production and the knowledge production that occurred within it and it is closely linked to both. It is important to note that because of the focus of this study on learning, one shall look into the representation; given that during the printing several considerations and decisions have taken place such as solution of printing problems, choice of materials or options for use. For Woolgar (1999), representations and object are interdependent, and objects can be understood only through their representations. Here, one might parallelize the building of an object by a 3D printer to the construction of a building: Gieryn (2002) perceives buildings as items that can be (re)interpreted as they communicate stories and they create representations when one dismantles the buildings materially and semiotically. Exactly the same analytical view can be used for the 3Dprinted products.

3.7 Summary

Closing this chapter, it needs to be clarified that 3D printing is a multifaceted activity which includes various knowledge practices with many possibilities and thus the venture to relate it to learning turns out to be complicated. However, the sociocultural theory analyzed earlier, the different analytical concepts of bricolage, mediation and representation as well as the discussions on Wartofsky's artifacts and on modelling can provide us with all the indispensable tools in order to build this study. The two concepts of artifacts allow to perceive 3D printing as an object while the two concepts of mediation and representations allow to perceive it as a process and object that offers opportunities for knowledge creation through the diverse knowledge practices. Arguably, by using a 3D printer knowledge is mediated and represented. Amongst all the different theories and concepts, it is extensively argued why these ones are considered as the most relevant. This does not mean that any other undertaking would be irrelevant. Nevertheless, this choice depends on the focus of each research analysis. Furthermore, this theoretical framework leads to specific decisions for the research design and justifies the best alternatives for the data exploration.

The selection of this theoretical context leads to a certain thematic analysis of the data which canalizes both theory and analysis with the research questions. The different artifact functions for example lead to the conceptualization of how the 3D printing process takes the role of all the different kind of artifacts through the knowledge practices that happen during the process. In addition, tactile learning and materiality are themes driven out of how knowledge is mediated and represented within the 3D printing process. Finally, the design stages function as a guide for the different knowledge practices emerging from the use of 3D printing. Hence, the choices in theory build the frame for the elaboration of both the methodology and the data analysis.

4 Research Design and Methodology

The pre-mentioned research questions are to be tackled by an explorative case study in a specific robotics' prototyping course at a research university Norway. The methods that will be used are complementary. The case study was chosen due to the fact that there is only one course in the university that uses 3D printers systematically. It is also most efficient for the time and place availability given for a master thesis. Similarly, a case study is appropriate for the research questions, as they focus on a specific setting or case and they also ask for an in-depth analysis through participant interviews and observation (Bryman, 2012). The core as in the course is used as a case and within that I followed different processes with a certain number of students, observations and interviews, while for the analysis specific participants were selected according to the most fruitful data.

A cross sectional design was considered as well, by adding observation and a bigger sample variety (Bryman, 2012) but was discarded due to practical restrictions such us the limited number of students and the limited time the researcher has available.

4.1 Choice of Design and Research Methodology

In this part of the study the methods that are being used for the collection of data and the design will be analyzed and justified. Since the problem under investigation is how the 3D printing as a process and a tool can aid learning and what kind of challenges exist within that, specific kind of data is needed.

The study is employing qualitative research methods. This methods approach allows for a more conclusive and inclusive analysis of student learning through interacting with 3D printers than a quantitative study. The qualitative approach is also implicit within the research questions, as they are all explanatory and of more general nature; both ask for a deeper insight into the way students work with 3D printing and learning. As Bryman (2012) states, in order to examine the social world, there is a need to approach it through the perceptive view of the people that are being studied and their reflections, as they are a part of it. Thus, the research questions of this paper ask for a qualitative approach in order to be answered in the most fruitful way, because learning is to be seen through the sociocultural lens.

The research methods used for the research are a series of participant observations and open interviews as data collection methods that will be further explained below. In addition, several data are being used, more specifically the course curriculum, photos taken by the researcher during the process of designing and printing. Yin (2009) refers to several characteristics of a case study such as the examination of contemporary events, as in learning in relation to 3D printing, but with no manipulation of the participants or the conditions, as an experiment would require. The case study can also be differentiated from history methods by introducing two more data collection techniques: direct observation and interviews of the people who were observed (Yin, 2009). These are the exact methods this study is using in order to understand how 3D printing can provide opportunities for learning to the students of the specific course. Another distinct characteristic of the case study is the use of different data collection methods, as documents, interviews and observation used in this study (Yin, 2009). This variety of sources leads to another case study feature: the triangulation, which in addition strengthens the reliability of the research results.

One point can be considered as differentiated from the case study concept and that is the embodiment of ethnographical aspects in order to best serve the research needs. The term ethnographical aspect refers to the participant observation as a data collection method which will be explained in the next part.

The participant observations with the ethnographic element as well as the interviews are also in harmony with the analytical framework which actually led to these choices. The socio-material perspective calls for observations and the need to follow the students along in order to see what kind of knowledge resources and materiality they used and how they used it. Without both the participant observations and the interviews one cannot get such a deep insight into the socio-material perspective, because both methods opt for talking to them and have a constant and more holistic image of the process. For materiality, it is important to follow up how learning happens and so it was considered important to add the participant observations.

Observation is considered as the best way to get a better insight into the way students interact with the process of 3D printing. Participant observation is the best way to understand how an environment functions, as it gives the opportunity to the observer to become a participant of some kind. Silverman supports this argument clearly when he mentions that one should participate than just observe from afar, because in this way he/she gets an experiential understanding of the object of observation (Silvermann, 2006). The observation is a method that will provide information on what kind of knowledge becomes accessible to students and to what extend this learning happens with awareness. Hence observation can be a useful tool also for exploring the concept of implicit mediation.

It is important to understand that researching learning is a very special case where the researcher needs to perceive how the participants think and react; thus, become a part of their world, which can be managed with participant observation. As Bryman (2012) notes, participant observations allow for the researcher to be introduced in the social world he wants to examine so that he can acquire a deeper knowledge of the culture of the specific social group, while qualitative interviews give the chance for a flexible source of data where the focus is on the interviewee's approach of the phenomenon. Yin (2009) also highlights the advantages of a participant observation; having the perception of an "insider" which allows for a more precise framing of the phenomenon, the possibility for manipulation of events such as the meetings of the participants and further manipulations available only in the participant observation, such as the use of documents, records and interviews. Another important argument by Yin (2009), concerns these manipulations that may lack precision in comparison with experiments, but on the other hand they offer a wider diversity of collectable data.

Interviews also provide a complementary view on the knowledge students acquire through the process of 3D printing and the influence of the artifact construction in their learning. On the opposite site of observation though, this is a tool to explore explicit mediation, on what students consciously learn during the procedure. The questions are open such as: "How do you value the use of 3D printing during your course?" or "How do you think that the use of 3D printing influenced your initial ideas during the constructing process". With such questions, directions are provided by the interviewer, while students are motivated to respond freely and contribute to an internal and rich approach of their own learning.

An interview is the main tool of a case study according to Yin (2009). He argues that a good interviewer can have a really good insight in the case he/she is researching along with information from the past or other that is considered relevant. In the present case for instance it is valuable to know if the students have worked with 3D printing before in order to understand possible difficulties they might have. Nevertheless, Yin adds that "*interviews should always be considered verbal reports only"* (Yin, 2009:108). Arguably, interviews reach as far as the verbal expression and at this point it is understandable how the participant observation not only enriches the data but offers validity further from the verbal data.

Arguably, interviews are a highly important part of this qualitative research especially due to the nature of the research questions. As Bryman (2012) underlines, with the unstructured interview there is more focus on the interviewee's point of view and it can be a highly flexible technique in matters of question variety or clearing up discrepancies in answers.

4.2 Selection of Participants and Recruitment

In order to serve transparency reasons, it is important that the process of collecting data is described with details and thus is clear and understandable for the external reader. The course is a master level course and the researcher addressed all the students of the course for participation. The 3D printers were used during the course for the construction of robotic particles for the final assignment the students will have to deliver. The maximum number that can work on each assignment is two students. The course is divided in lecture hours (4 hours per week) and laboratory hours (4 hours per week).

First of all, the Norwegian Data Protection permit was acquired in order to proceed with both the observations and the interviews. For the purposes of the research the researcher contacted first the professor of the course of rapid prototyping in the University of Interest in Norway, who also gave her a tour on the laboratory room and the 3D printers explaining how each one works and the differences between them. Then, during the first class of the semester the researcher explained to the students the purpose of the study and invited them to participate after signing the relevant consent form. It was made clear to them that the participation is voluntary and they can interrupt the cooperation at any time. Nine students offered to participate and six of them were working in groups of two. As far as the participants are concerned, there were eight male and one female participant and only one of them had previous experience with 3D printing. Nevertheless, all of them had some previous experience with other CAD software. All participants had to sign a consent form which was accompanied by an information letter (Appendixes 4, 5)

4.3 Data Collection

First the observation scheme was developed. There were more columns but in the end, some were considered irrelevant and were not being used. There is one column under "date" where there is information on the number of session and the date the observation took place. Originally there was supposed to contain also notes on the time span of the activities but many students were only partly working on activities during the observation hours and also it was not considered important information. In addition, there is an “activity” column which shows what kind of activity was taking place as for example ‘designing foot’, ‘printing a gear’ or ‘watching tutorials’. Then the “knowledge resources” are described which are considered important in the materiality context: these can be tools such as screws or motors and also software or printers, books and internet sources. Finally, there is one column for “comments” students made and one for “personal notes” that were considered important according to the empirical context. These two were originally in one column but were divided for easier access and analysis of the data. While taking the notes the researcher was opting for what is important, having in mind the concepts of mediation, tools and representation and the socio-material perspective. The observation scheme can be found in Appendix 1.

In the beginning the researcher used an unstructured interview with the professor of the course on how he perceives the pedagogical purposes of the use of 3D printing. The interview is considered as an important part of the data collection because the tasks are organized by the teacher and thus light will be shed to the pedagogical intentions of the use of 3D printers. It is important to note that because the course is being organized by the teacher, this organization constitutes an internal part of the students’ learning. Moreover, the professor contributed essentially by expressing his own ideas and observations from the class. The conversation was quite fruitful; the professor had a lot to add by himself and elaborated different ideas relevant to the problematic of this research. The interview guide was proved quite helpful and if there was terminology that was unclear due to the different nature of the two fields, then the researcher would explain further. The interview guide for the professor can be found in Appendix 2.

Then it was decided that only the first project of the class would be followed with observations due to time limitations. 13 observation sessions took place each one with a different number of participants. Some of the participants were not attending the laboratory always; usually for each observation 4-6 people were attending. This happened due to the fact that a big part of 3D printing is actually designing which many of them did out of the laboratory room. Also, sometimes the participants were entangled in other processes for the project, irrelevant to 3D printing, such as programming the robot. During the observations, most of the students were describing what they were doing by themselves and if there was any problem the researcher would ask some questions on the matter. Thus, the observation guides have two columns, one of notes and one of comments from the participants. Also, when it was needed photos of the process where taken for a better understanding of the comments. During the observation, several notes were taken in respect to the interview guide also. The way the students were working sometimes was bringing up interesting subjects for the interviews that were not thought of, such as the resourcefulness needed to solve designing problems. In any case the number of participants and of observations is considered adequate for the present research as the aim is to provide an exemplary situation; not patterns but instances when learning is happening. The data aims to illustrate the process and not identify.

For the purposes of a better understanding of the process the researcher followed up all the lectures that took place and was provided with all the class material. The class attendance helped a lot in getting a better insight on the tasks the students were assigned to. In total, the process of observation required eight hours per week divided in two days. This equals to two hours of lecturing and two hours of laboratory work each day. Some lectures were cancelled due to curriculum changes or health reasons and then the observation in the laboratory would last four hours. Some students used to work longer than two or four hours per day but the research was not able to attend further due to personal obligations.

During the observations, also many photos of the process were taken. According to the theory of materiality pictures are considered important and occasionally more important than words in order to show the different materials and designs. The images taken during the observations are an internal part of this study. These photos can show the process and the evolution that took place from starting to design until printing in a way that a huge text would be needed to provide us with the same result.

The interview guide for the students (Appendix 2) was developed after the observations were finished. During the observations, the researcher noted different behaviors that were thought as interesting and were used as a source for the interview questions. The interview guide was not constructed as a strict interview plan but more as a well of questions that gives to the participants the incentives to start talk and elaborate their ideas on relevant subjects and as such it is a set of open questions that aim to not limit the interviewee in his/her answers. The interview guide was set based on the research questions and further on the observation notes and it can also be found in the Appendix 2. The students were contacted in order to arrange appointments for the interviews. The interviews took place in couples according to which students were working together. The participants 3 and 4 were put together in order to have a set of 4 interviews in total due to the fact that in this kind of mini-groups, the conversation made it easier for the students to complement each other’s statements, fill in stories and examples, and thus provide richer information. Their projects were totally different in many ways and thus it was considered as an interesting combination. The participant 5 was not able to attend after all up and he was therefore not included in the data set subject to analysis. The participant 8 was decided that he would not be interviewed because he was mostly working in different times than the observation sessions. Hence it was considered that his contribution would not be important for this study. As mentioned already, all participants signed written consent forms the first day before the observations started. Each interview lasted for about one hour and a total of four interviews by students took place and were transcribed. During the interviews, the researcher tried to intervene the less possible so that she would not interrupt any ongoing thoughts of the participants and tended to guide the conversation only to the point that there was a clear subject of conversation. The interview guides, found in Appendixes 2 and 3, were used to suggest interesting points and if needed the interviewer was making further questions on certain points she found interesting during the observations. In total five interviews were realized with eight students and the professor, of approximately one hour of duration each. All he interviews were transcribed word by word.

4.4 Analytical Approaches

After collecting all the data, the researcher coded and categorized it in themes driven from the analytical framework. Central themes were taken from the theory, while subcategories were created according to the collected information. The following chapter presents the analysis and generates the findings. In order to reveal how the 3D printing allowed students to construct and explore knowledge, the data was coded using theoretical concepts for how knowledge was worked on and within the process, such as mediation, representation and tools.

First the observation data was coded using the relevant theory concepts of mediation, representation and tools. However, 3D printing affords several ways of engagement which also allow seeing it as a process. In this way, there are more knowledge practices from a design process that can be divided into developing the idea, decomposing the idea, design for themselves, experimenting and testing out, examining materials and visualization. A 3D printer can serve all the purposes of all the different types of modeling and designing as mentioned by Maier et al. (2014): capture ideas, get insights, complete a design of a product, elaborate this design, manage the design process or find out the consequences of the solution the design is aiming to. All these processes as a part of the wider process of 3D printing were considered while defining the knowledge practices that came out of the coding. These knowledge practices from designing lead back to the central codes as they show how a 3D printer mediates, affords, represents knowledge.

Later the same codes were used in order to code the interviews as the aim of the study is to keep observations and interviews together and check how the interpretation of the two means can come together to reassure the same results. In the few cases that the interviews were introducing totally new categories, new codes were added but of no special importance. Both the texts from the observations and interviews were coded entirely.

4.5 Credibility of Research

For the Quality Considerations of this study the researcher will use the two primary criteria of Lincoln and Guba (1994) that are widely used for assessment of qualitative studies and thus easier to understand and consider.

First there will be a focus on the four different trustworthiness criteria. The study does complete the credibility criterion as it is carried out according to the principles of good practice and the results will be made available to anyone in order to understand how the researcher perceives the social world. Also, the credibility of the results is complemented by the triangulation of methods, because both interviews and participant observation will be used to answer the research questions and by the added value offered by the professor's interview. Furthermore, both in interviews and observations the researcher was participating when necessary in order to adjust the interpretations and make sure she was not interpreting according to her own way of thinking. For instance, check questions were asked to the participants to ensure that her understanding was correct during the observations and interviews were used to triangulate data and secure the interpretations. In addition, all interviews were recorded and transcribed in order to avoid any loss of importance data and strengthen the credibility. Credibility is further reassured by the pictures used in the study which are taken during the observations.

Transferability, the second Trustworthiness criterion will also be covered to a big extend by thick and transparent descriptions that allow for deeper understanding and hence judgement of the results as well as possible transferability of the findings to other studies or fields of research. The study can be transferable in a way that the same interview guides and observation schemes can be used for further research. The specific subject is relatively new in the world of research with a small amount of already completed research material and very few of that concerning learning. In this way one could argue that the transferability is higher as it leaves open possibilities for further elaboration.

As far as dependability is concerned, all processes are described and justified with transparency and in this way, they are accessible for peer feedback and conversation. In addition, in the Appendix there are available the interview guides, the observation schemes and the NSD form.

The confirmability of the study as the last trustworthiness criterion is a vaguer notion that can be interpreted subjectively throughout the research. Given that both the interview process and the participant observation ask for the direct communication between the researcher and the participants, the confirmability cannot apparently be very high. Nevertheless, these two methods are considered the best for the acquisition of all the important information for the specific research questions and for the researcher to become a part of the social context she is exploring. Furthermore, the researcher can decently assure for the most possible absence of any personal bias and views in the study.

Last but not least the Authenticity of the research, aka the second quality criterion by Guba and Lincoln is considered to be covered in a high level. Although the fairness is not that high due to the fact that the participants are all from the same course and master program in the same university, the professor’s point of view adds value to it. Besides the ontological and educative authenticity are considered to be quite high, given the fact that through the observations and the interviews the participants have a better understanding of their learning and they come to think of how they might acquire knowledge when using 3D printing, something that they might have not thought of before.

Reviewing the quality value of the research, one can notice that it lacks in points such as the confirmability or the fairness, but both are justified by the wider frame of the study and reasoned by the chosen methods.

4.6 Ethical Considerations

Although this study does not deal with very sensitive information, measures are taken to insure the participants' ethical rights. First, all of them will take part anonymously. Due to absence of personal information, tracing back answers to individual participants will be almost impossible. Even if the University and faculty can be traced down it is hard to identify the participants and they have been informed for such a possibility.

Secondly, the participants are fully informed about the different stages of the study and they have been made aware that they can leave it or refuse to answer to questions without any consequences for them. An informed consent form has been signed by every participant (Appendixes 4, 5). It is really important that the participants were aware of the voluntary character of their participation. The consent form can be found in the Appendix as well.

Thirdly the present research project has the approval of NSD (The Norwegian Center for Research Data) (Appendix 6) which has examined all research planning and methods and the possible ethical considerations in order to approve the research project. The process is obligatory in Norway at any case that the researcher gathers personal data and reassures the research ethics.

The possibility that students might feel pressure during the observations by the presence in the room has been considered. However, this has been deemed very unlikely and of little impact on the students. This was double checked with the students by talking to them during the first class of the course and by describing intrinsically to them the researcher's role in the room. It has also been taken into consideration that all of the participating universities offer psychological counseling for students. Even the students that did not show up received one and only message that was asking if they will participate and they were not contacted again.

Concerning issues of disinterestedness, this study is explicitly not done to improve or criticize any teaching methods or students' learning. The researchers are not affiliated with any of participants taking part here. Also, there is no intention for any kind of advertising throughout the study. The results of this study will be made available for everyone.

4.7 Summary

Summing up, this is a research conducted in line with the qualitative method prerequisites, given that the aim is to explore students' perception and knowledge creation. In total, two data collection tools were used; participant observations and semi-structured interviews. The participants expressed their interest voluntarily after being informed on the aims of the research and signing a relevant consent form. First, the observations took place in a time span of three months and by the end of the observations, appointments for the interviews were set. All the data set, both from the interviews and the observations was coded according to the theoretical concepts and how these answer back to the research questions. In matters of credibility, two primary criteria by Lincoln and Guba (1994) were used to show how this research offers relatively high credibility. Last but not least it has been thoroughly explained how there are no serious ethical considerations emerging from the study.

5 Data Analysis

This chapter will present the analysis supported with examples from the data collected both during interviews and observations. It starts with an overview of the course structure and the assignments students were to work on, to situate the robotic project the study focuses on in the wider course context. Then illustrations of the design processes of a group and a single student are presented in order to depict the basic steps of designing and printing and how students can approach these differently. Based on this, section 5.3 gives a thematic presentation of the analysis, focusing on how the 3D printing provided opportunities for learning. The structure of this part follows the research questions and it is mostly informed by the interview data. The different themes chosen to answer the research questions are in line with the theoretical background and concern knowledge practices, knowledge forms of materiality, technological affordances of 3D printing, Pedagogical challenges and assemblages. The chapter ends with a summary of the content analyzed.

5.1 The course Set up

This is a small introduction to the course structure and set up, in order for the reader to have a clear idea of how the 3D printing was used in the context of the course. The course was organized in three projects but this paper followed up the first one of them due to time limitations. The first project is focused on making a leg-ed robot which can walk. This is the project that has been followed up for the purposes of this study. The students have to design the robot on a CAD tool, simulate the walking part and then print it, assemble it and program it. Programming is the only process not followed because it was considered irrelevant to 3D printing. By the end of the project a presentation takes place where each student demonstrates his robot and can see the other robots in action as well. The second project is to use another CAD tool, a more *"artistic one"* as the professor said to make wearable sunglasses *"just to open the possibilities a bit out of robotics" (Professor, initial interview).* The last project focuses on CNC-machining. The participant observations concern the robot project.

There were two weekly hours of lecture which were focused on general information concerning the 3D printing (such as different materials, ways it is being used on the field), on suggesting different ways one can work and on showing different moving mechanisms for the robots. There were another two hours per week where the students would work on different designs on the CAD program with the professor in the class so that they could resolve any problems coming up and discuss their designs and their mistakes. The professor explained how the hours of the course are structured.

> *"…also two hours this year for exercise lecture-like to sit and try to design while I am helping them…walking around helping them…" (Professor, initial interview)*

After the lectures, there were four hours weekly in the schedule where the students would be divided in two groups (Monday and Tuesday group) to work in the lab, designing and printing. However, most students used lot more than four hours per week in the lab and the lab was open for them at any time they would want to work in. The project this year took 15 weeks to reach the Demo day –Easter vacation included- because of 4 weeks of cancelled lectures due to health issues.

The project (as all the projects in the course) was assessed with pass or fail and it was not graded. This fact aligns with the purpose of the professor for the course which was basically that the students will become more creative and have fun, recognizing the function of the 3D printer both as a secondary and tertiary artifact. On grading, he stated:

> *"-Do you grade the robots?*
> *Professor: No, it's all theirs, their product, their ideas.*
> *-And let's say that a student makes something that doesn't walk that well but it's a good try...*
> *Professor: I use to say that you can choose either to make it safe, simple and safe and then it should work… or you can take a chance to make some really spectacular things and if it's not working, it is perfectly ok." (Professor, initial interview)*

The professor's pedagogical vision on knowledge creation is reflected at different points during the interview. Through the data analysis there are some of his quotes on how 3D printing can be motivating and change the way someone is thinking, boost creativity, create stronger connection between thoughts and ideas or stimulate tactile learning. Below he refers in an arguably interesting way to how 3D printing can open one's mind and provide him/her with confidence for his/her own ideas. In addition, he argues that 3D printing creates a canal between ideas and reality: this is to say that 3D printing makes you see your ideas and realize if they can come to life or not and which are the reasons:

> *"I hope it's open up their mind. And I hope it gives them confidence. That they can actually believe in their thoughts and ideas… it's peeling off all the far ideas that could not work in real life. So, it's about being to the point also and at the same time see why things are not working, why their ideas are not working in real life and just experience the difference between their mind and the real world." (Professor, initial interview)*

The professor's emphasis on creativity is also visible through his open instructions for the course; students were to make a walking robot for which they should make most of the parts by 3D printing, but the design and partly the material selection was up to them as long as they present something that moves (even if not with total success) by the end of the project. The professor commented a couple of times on how the students shall be free and creative:

> *"…They have to 3D print. To be able to go through that process and they are designing this walking, this leg-ed robot and they are free to choose the design. They can make everything that it is possible to make. And then we see all kinds of different creative expressions of course… that's nice, that's the important I think of the course…To be able to be free…to be free in your mind. And not limited… I think it is more satisfying for me to stimulate the creative part. (Professor, initial interview)*

This idea of giving freedom to explore and making decisions in their own way, was also recognized by the students. As one student stated:

> *"…One of the things I like about this course is that it kind of throws things at you and you just have to solve it in your own way. It gives some of the tools but we have to picture out pretty much on our own all the rest. So that`s one of the things I like as well. We are independent." (Participant 9, end interview)*

The freedom students enjoy stimulates them also to search by themselves and use several online assemblages in order to find information or solutions. More precisely, the participants used to assemble online sources when they had to find information on any topic, or solve a problem. All of them agreed during the interviews that they did not use any printed material, but online communities or video tutorials searching by themselves and finding out very specific information. Moreover, most of the students used short guide-videos uploaded by the professor in the course website as a support for solving their problems. Those videos repeat processes students have done already in class and some participants used them also for practicing. Participant 5 explains how he used them to practice and how he found them useful especially in the beginning.

> *"We have Professor's lectures and then we have professor's examples that we used in the training exercises which is with him standing and...going through the same examples that he's had already done in class. So, you can just go through those examples on your own, without having to watch him do it again…These were very helpful short videos and but I don't think I looked too much on the other stuff available…" (Participant 5, end interview)*

Participant 10 stated that except from the course's video tutorials, she also used online ones but her teammate, participant 7, argued that the course's tutorials were better to watch "instead of these other ones" because they were shorter and more focused to specific tasks.

The course included several opportunities for supervision and support, students could get help from the professor during the lectures and from other master students of the previous year during lab hours.

This section provided the reader with a better understanding of the course context and the use of 3D printing for the projects. Now a short presentation of two observation processes will follow up.

5.2 Illustration of two design processes

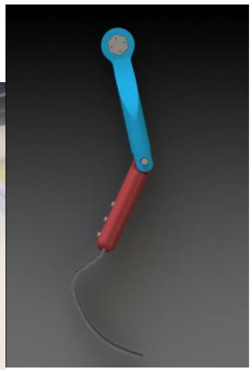
In this section of the thesis, the projects of two different groups will be described with the relevant photos so that the reader can have a clear illustration of the process. It has to be mentioned that the participants were changing lots of things during all the different phases which cannot be depicted and both teams started by sketching on paper with pencil. However, the illustrations below give an overview of the basic steps in the students' 3D printing process and shows how two different design ideas were materialized during the process and led to a final product. The two processes were chosen based on the collected observation material and due to their different way of developing the project, to show two possible variations.

Process A

Two students were working in process A. In the beginning, they discussed in order to decide what type of robot they wanted to make. They were balancing between a typical robust robot image that would move slowly and a humanoid runner which they actually chose. In the pictures 1 and 2 one can see test-prints they made of the main body and the lower leg.

Picture 1
(Personal archive)

Picture 2
(Personal archive)



Picture 3
(Personal archive)

In the beginning, the participants had to design all the different parts of the robot separately and then mate them together later. In both processes students started design from the lower to the upper part. The pictures 3, 4, 5 depict different phases of the designing process. Picture 3 was taken during week

4. It was the first time where the students connected most of the parts of the leg together and could have this more complete image of how it will look like. The picture 4 was taken in week 7. Arguably there are quite some changes from picture 3. The participants by that time had designed and added the piston as a moving mechanism and had completed the mating process in Solidworks. Picture 1 was taken during week 3 and picture 2 during week 4. As they said during the observation they printed the part of the leg (picture 2) in order to "*see how it is, how it feels, how it walks…*", as well as the miniature of the body (picture 1) which was printed to give them a realistic image on how the body will be.

Picture 4
(Personal archive)

Picture 5
(Student's archive)

Picture 6
(Student's archive)

The pictures 5 and 6 were taken during the last week and depict the final product in the software (picture 5) and in real life (picture 6).

The robot had to be designed part by part before putting all of them together in one common and final design. The two students had to fix successfully lots of errors and malfunctions during the project. Especially they had small designing malfunctions before printing: sometimes parts were overlapping or other times they couldn't achieve the desired shape. The knowledge mediation during the making was not only explicit but also implicit as they were finding out how they could or they could not use several materials, software and shapes, not always realizing that they were acquiring knowledge. The two participants experimented a lot and tested out different shapes and printers in order to reach the final product as they commented during the participant observations:

> *"It's far from a final solution. We were just messing around, trying to make it look right. Regarding the gear it was too complicated, so we went for a simple hexagon which will connect the motor to the hip." (Participant 1, informal talk)*

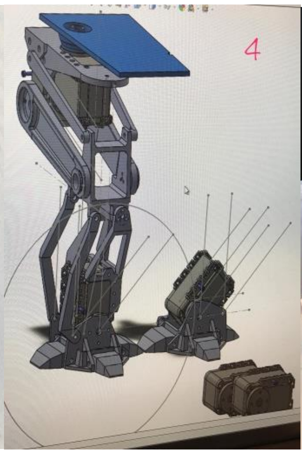
The down part of the leg especially required flexibility in order to bend while walking and it shouldn’t be too short so that the robot wouldn’t fall to the front. This led them to try out different materials and so printers, such as fiberglass, to find the best solution. Also, the upper body in the end had to be printed in two parts due to its size which required long printing hours. Another important realization for them was how a software simulation can differ from real life, although it can look quite convincing.

The original expectation to make a runner was not met. The results were very satisfying though, as the robot managed to walk successfully and the designed parts were 3D printed and assembled to this humanoid robot as they called it themselves.

Process B

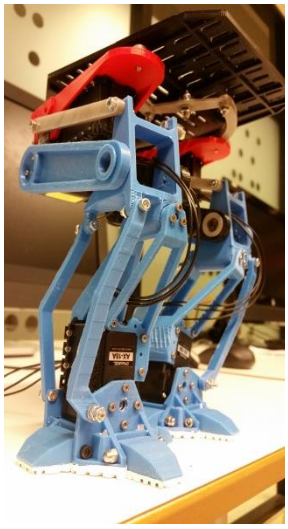
Process B was consisted by one participant who, in contrast to process A which moved towards a humanoid curvy design, aimed to something closer to Sci-fi robots from movies as he said later in the interviews.

Picture7
(Personal archive)



Picture 8
(Personal archive)

Picture 9
(Personal archive)



Picture 10
(Student’s archive)

As shown in the Picture 7 which was taken during week 5 the participant started from a straight leg which he realized through software simulation that would “tilt and fall”. The designed was already containing lots of details and different small parts compared to other students. On a discussion during the observation he mentioned that:

> *“Maybe my design is too complex so maybe I will make it simpler”* and later on he added on how he could not see the anomaly that *“I can think how it can move but for actually seeing how it actually moves that is a different thing” (Participant4, informal talk)*

He went on to his second and last design (Picture 8/ week 7) where the feet have a bending point to keep the robot stable. For this design, he sketched a lot on paper and did lots of calculation in order to find how to construct the right angles. It was interesting how he commented through the process on visualization, during the observations. First on how the object gets to be shaped in the mind:

> *"For me working in 3D printing means I have to think first in 2D and then you can extrude and develop" (Participant 4, informal talk)*

And then on how the ideas get to be visualized:

> *"It's nice to see your ideas getting into the real world and not just stay in the computer. Already in the software you can see the 3D design and check out how it works…It's really nice. You don't have to necessarily 3D print it then. But 3D printed it is the model in real size" (Participant 4, informal talk)*

In Picture 9 taken in week 8 there is a photo from the assembling procedure were the lower parts of the feet are already assembled with the motors in place.

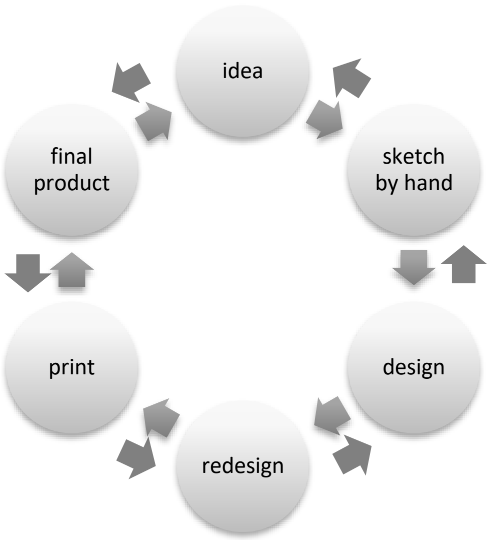


Table 1 Basic Steps Students Followed During the Observations

He went as well through lots of errors as well and different realizations on how to add new parts in order to assembly the final robot and keep the motors in place. Mostly the changes concerned challenges that were coming up when the robot was supposed to walk in simulation. There were many small parts which made it hard to imagine always how they would cooperate within the walking pattern. Nevertheless, having small parts is definitely an advantage as one can easily make small changes and print them again relatively fast. His project was also successful as the final robot (Picture 10/week 15) managed to make its small steps. In order to move the feet would go first to the sides and then to the front, which required two pairs of printed and assembled joints for the knees.

Above there is a table that shows the basic steps followed by most students as observed and noted during the sessions and how they are connected to each other: There is a first idea which they usually tried to put on a sketch on paper, then they started designing on CAD, finding errors and redesigning for a better result. Than they started printing, finding more errors, redesigning and printing again until they reached the final product.

5.3 Thematic Analysis of how 3D printing provides opportunities for learning

For the data analysis, there will be used a thematic structure in order to answer the research questions. This part of the thesis, will begin with a presentation of our data material. The data will be presented under the relevant categories and can be understood as a summary of each theme. The themes emerged out of the collected data, but the research questions directed the process significantly. Arguably the collected data was connected and corresponds well to the research questions. There are many different opportunities for exploration and knowledge construction through the 3D printing process which will be presented in the separate concepts that respond to the research questions; assemblages that are being recruited for knowledge creation, ways that 3D printing engages students to knowledge practices, ways that 3D printing provides experiences with different materials and knowledge forms, technological affordances and constrains of the 3D printing that matter for learning and pedagogical dilemmas and challenges. Of course, all these themes will be presented under the perceptive eye of the students and the professor. One final theme connected mostly to the challenges met throughout the course will be challenges and dilemmas on the pedagogical ground.

5.3.1 How 3D printing engages students in knowledge practices

One way to facilitate knowledge exploration in this course is to engage students in various knowledge practices which take place during a process or while using a tool, such as: designing, testing out, printing, simulating and assembling. The participants mentioned different practices such as design and redesign, simulation and visualization, printing or even testing out. Through these practices knowledge is being mediated and students get the opportunity to explore different aspects of 3D printing such as materials, knowledge resources or shapes.

One of the most common knowledge practices, thoroughly analyzed is that of **designing** as part of the 3D printing process. In the beginning of this phase designing starts as a tertiary artifact where students imagine the world in the making and most of the times they have to explore available knowledge resources in order to find inspiration. One student commented on the process with an emphasis on bricolage as he mentions how they had to make a design for the project that would work with certain resources. He starts with how he got inspiration and which were his initial ideas; how he leaped from one to another. This is a process related to the implicit mediation as the mental decisions are not quite clear but he tries to describe how they happened:

> *"Well, we discussed…and then I started thinking something like frog, like frog jumping thing but participant 10 kind of wanted to do a spider and I thought a spider would be cool too. And then I kind of tried to look at different ways that spiders move and then I also looked at different spider robots that were available and seen that they had a lot of complexity and then basically trying to picture out something that was in the limits that were given in the course because we couldn't have as many cervos as we would for a typical thing. That's kind of the basics" (Participant 7, end interview)*

However, the other participant of the team does mention the difficulties of designing a whole robot from a zero point which led them to use another design they found online. She explains though that although the design was readymade, they had to make it their own as they had to design everything themselves in Solidworks and then print and assemble it. She actually stated that making something original in the context of creating your very own design might be too complex. In her words:

> *"Yes, I think it was a good idea to just use something that was already existing but sort of make it on our own. Because we had to design the parts after all. It's really hard to make something original" (Participant 10, end interview)*

What most students gave emphasis to is that the 3D design shall start simple and then one can build on it and not try to make a complex idea work immediately. Participants 5,9 were discussing during the interview how initially they began thinking of the final curvy shape when they should actually start from the opposite side, by setting the first straight lines. This statement is also connected to the implicit mediation as it describes an internal mental process which at first was not conscious. During the process and as knowledge continued to be mediated the mediation became explicit and they ended up having a clear idea on how design shall start. This is what they acknowledged during their conversation:

P.5[4]: "Yes we started first inspired by biology without thinking about the curved stuff. Without thinking if that mattered or not. Because it would look better. And that is not necessarily a god thing when you do prototyping? You might want to start…"

P.9: "From the other end!" (Participants 5, 9, end interview)

Participant 2 agreed to this idea and emphasized on simplicity and how the first idea shall be decomposed and built gradually. To that he mentioned:

"But then I realized in the rapid prototyping, it's not always necessary to overcomplicate it. You can start with an idea and then go slowly on it, change on the way." (Participant 2, end interview)

While discussing learning all students mentioned that during the designing process they had often to fix errors and even start again and redesign from the beginning. Many of them agreed openly that they actually constructed some kind of knowledge through this process even if that was designing by itself. Participant 5 stated during the end interview that *"we made another version and we designed and redesigned and we designed and redesigned…"* and when he was asked if there was anything he learned from the design process his answer was "*to start again*". To that agreed also his teammate, participant 9, who acknowledged it as a good point so participant 5 elaborated further. As he explains during the time that one elaborates a design on Solidworks errors shall be found. However, in order to fix those errors, you have to locate them in a very long chain of tasks. In this way, it can be just easier to just start all over again and try to give more flexible parameters that will entail possible future changes, if the design is not fixed to all its details. He explained:

"…Start making something and then we get to the point that this isn't right and then try to fix it and then just find out that it's just easy to start again based on what we have done but just do it right in the beginning with flexible dimensions that we can change afterwards and variables so we can change things more easily. Because we ended up making something that we couldn't change. If we wanted to then we had start over." (Participant 5, end interview)

As one can see here students need to think of the final product and imagine all its details. This illustrates how artifacts took a tertiary function in the process by imagining the world in the making. Then the ideas are put in the software and the artifacts take a secondary function which is to represent students' ideas through the 3D design. It is a learning process where the mistakes and faults function as explicit mediators which invite the designer to realize the best way to make a proper design. For that one might have to start over and over again, achieving a better understanding of the process each time. Participant 9 said on that:

[4] P.= Participant

> *"So, it has also been a learning process for Solidworks. Starting over again, because you can make a model at first and then you realize it is possible to make it like this and use these relations and make it proper actually. So, then you start over and you have learnt that." (Participant 9, end interview)*

To the same question on learning opportunities during designing participant 1 gave a similar answer but he adds that designing on the software did not affect much his creativity. Each time one designs the process becomes faster and soon you know how to go back and correct the mistakes. In this procedure creativity might not be of relevance, as it is more about learning how the software works. He elaborated on that:

> *"Designing something again and again, much quicker I think. We made a lot of errors and had to go back. But it's a new software and we don't really train our creative mind a lot… Yes, you have to go through it again. (Participant 1, end interview)*

Seeing an object designed from all the different angles in Solidworks brings up errors people might not think of. Then you are invited to go back to your thoughts and elaborate the error and fix it in the CAD tool and then have the same problem again and again with all kinds of errors until you have finally perceived all the various possibilities of your own design, and you can print it. In this way, the errors become mediators of knowledge and the print comes to represent whole knowledge processes that have happened in order for it to be produced. The professor explaining how the students express their ideas through designing, talked about visualizing the product from several angles which let them get in and out of error "loops" in order to create something functional in the end. He commented:

> *Professor: "But if you can take it on to a 3D… a CAD program then and turn around the part on your screen and look at it from different angles, then something is happening, and you will see that the ideas will not probably work at all. So, then you can go back to your head again, change it and you have this loop between your head and your CAD tool. The loop can be… going on for a while, until what you think you are done. Yes. And then you can print it out. So, the next part of this chain is to print it out." (Professor, initial interview)*

An interesting point of view coming out of the different interviews, clear example of explicit mediation, is that many students, when asked if they have acquired any kind of knowledge during designing, they answered that they learnt how to design, or how to use the designing program and its different functions. For all the participants Solidworks was a new experience and for some the first CAD experience, which they think can be useful later on in a job environment. For the participants 7 and 10 by exploring designing they actually argue that they learnt how to design and how this can be helpful. Participant 10 gives an example on how she already came to see the usefulness of CAD when she used it for making a design her supervisor asked, for her thesis:

P.10: "Well, I never used a CAD program before, so that was completely new to me and I think it is really good that we now know some things about how to design things in 3 dimensions cause it might come in handy. I used it for my master thesis, because my supervisor asked me to design like a part in a CAD program. So, it is something that is probably useful from time to time, to know" (Participant 10, end interview)

Learning how to 3D design can be useful also in PhD tasks and it can actually be satisfying as one develops a further understanding of the software and can work on it faster each time. Participant 7 was the one giving an example on this. After printing two parts he realized they would not fit together and so he had to redo the design from the beginning which was demotivating. Nevertheless, by start designing he realized he could already be a lot faster than he thought he would as he was already familiar with the language of the program. He commented:

P.7: "I mean I definitely think it is something I will be using later on for my PhD work … just before Easter there was one part that didn't quite fit together in real life and then I was like this is too difficult to start from scratch…I was able to come up with a part very quick…and I was like really surprised how far I had come in these weeks. Well, I think I learnt a lot. I think it will be useful." (Participant 7, end interview)

Participant 4 also thought he mostly learnt how to manage Solidworks which was different from his previous CAD experience. Thus, he expresses a similar opinion when he was asked if designing helped him construct any kind of knowledge:

P.4: "Maybe some of the functions? Like me coming from having used another CAD tool before, these functions are heaven." (Participant 4, end interview)

There is a special feature in designing in 3D that permits to the mind to visualize not only what you already have designed but further than that, to realize any malfunctions and picture in your mind the future improvements; the next steps. Participant 3 emphasized especially on how designing actually helped him visualize the product. Imagining the world in the making shows how the 3D printing process activates the tertiary artifact function. He especially mentions how putting the design in the software helped him:

P.3: "it was much easier to go from the initial idea to where you have designed something and you can see that this might not work…it's easier to picture in your head what you want the next step to be. How you can improve…when you have the idea and you actually make it in Solidworks then it's easier to change your idea in the head because you can see that this is not working…" (Participant 3, end interview)

An important difficulty when you design a robot, or an object with many parts, and especially moving parts is that there are many subtle details that have to be fixed, quite hard to remember. On visualization, participant 4 brings a relevant example on how the 3D design can help keep all the small details in one's head and in the meantime, perceive the robot as whole. The software, he argues, facilitates the process of finding out what exactly one needs in between the details. His example refers to a part of a design where there was a missing screw but another part was overlapping with that, while moving, something that he realized when he tried that movement and he had to make the shape of the screw whole in the design so everything will fit later on. And so, he explains:

> *P.4: "…there was a part where I am supposed to have a screw…but there was a part that glides over that area, so I had to make the shape of the screw so it fits…this kind of details is hard to visualize in your head or even the whole robot it is hard to visualize…like I have an idea of what I want but not exactly and then in the 3D software you see what you need… when you have so much details, it's hard to think of everything at the same time, so when you are considering one thing it's easy to forget another" (Participant 4, end interview)*

Patterns and shapes are two aspects of the CAD tool that one explores better by using it. Hence, he/she can fix the problems in a better way, an easier one. Participant 2 expressed the same opinion as well on how the 3D printing design software assists students to achieve a better understanding of the shapes and the errors on the design:

> *"In Solidworks, especially in a shape, if you understand a pattern, fixing problems becomes much easier" (Participant 2, end interview)*

From shapes and patterns and breaking down complex forms there is an artistic aspect in 3D design. There is a mediation of developing a deeper understanding of how geometry exists within the shapes and how one shall start designing from the simplest of them. It is an inverted process when one has to take the original idea, break it into shapes and then start adding details again. There is a creativity boost from the 3D designing which gives the opportunity to explore the world of ideas, in a similar way artists do. It was arguably inspiring how participant 2 argued on how the 3D printing designing program helped him be more creative, out of his engineering world and understand how a bigger image can break into small shapes, connecting it to art. He explains how he never understood the artistic state of mind, how he had a difficulty in seeing the shapes around him, only until he started drawing. Then he realized how you make a shape simpler in order to start building on it. He elaborates further:

> *"Yes, if you see the geometry and you realize ok this is a pattern, I can do this one and this one. And that same concept, you can find it amongst artists for example…It was one gate for us to be a little more creative. And we lack that to be honest…that's a gateway for nerd artists …my girlfriend she is an engineer and an artist and she always talks about the shapes and she describes outlines… I never understood that…but when I started drawing 3D then I actually understood what she talks about. Before you start drawing, you look at the shape*

and you simplify it, you take the important parts and then you start working on it. I mean you start building. You take something complex and simplify it and then increase the details…" (Participant 2, end interview)

Another important knowledge practice which emerged is **testing out** the student's ideas in real life. During both the observations and the interviews, through 3D printing as in rapid prototyping, students have the opportunity to test out whatever they need to, with a low cost. Testing out helps them see certain mistakes and elaborate further to more efficient versions of the final product. Testing out is a part of the process where 3D printing becomes a primary artifact and the printed object is used as a tool for constructing knowledge. Most of the students made test-prints in order to test materials, or shapes, or sizes, or just to see how it feels as they used to say. On this, participant 5 mentioned that after printing a first version of their robot they could now that the next one was actually going to work. He describes that by making a test-print they could attach the actuators and see how they move and how or what they wanted to fix or change. It is worthy to observe how he uses twice the word interesting:

"…now it works well enough so that we know that basically the next version will work…so one thing that is pretty interesting I think is that we 3D printed our first version, and then we tested it and then we put up some actuators and saw kind of the flows of our design that we now want to correct. So that was an interesting process for me at least." (Participant 5, end interview).

Also, participant 2 commented that *"we even did some test runs like the torso or the lower leg to see how the different materials behave." (Participant 2, end interview)*, signifying how testing out allowed for material exploration.

Apparently testing out is closely connected to another practice; to **printing** itself, as already mentioned by participant 5, given that printing in rapid prototyping can be used not only for the final product but mainly in order to test out different versions of it. The 3D printer as a primary artifact is used to bring in life/print the given design, in line with Wartofsky's theory. There is a realization that function as a path from the implicit to explicit mediation. This realization concerns how one can use the printer also for testing out. This thought was expressed by participant 9 who elaborates on how during the course he came to comprehend the use of printing as a developmental tool, used to try out rapid prototypes and only for a final print. During the interview after analyzing this thought participant 9 connected all three mentioned knowledge practices as a chain of designing-printing-testing out which repeats itself:

"Yes. But one important point for me is that we could use the 3D print to short of get our minds around the design and see if it works. And it's pretty rapid to print it out on a 3D

printer. And that for me was a big lesson. That this can be actually used in the development process, not like that when is 3D printed then it's final. You can actually print, see if it works, print again and short of like have this process of design." (Participant 9, end interview)

These "failures" in printing as a testing out apparatus which allows for knowledge construction was mentioned by many students. They also emphasized in this "rapid" aspect of the tool, of the primary artifact which offers the opportunity of a fast response the testing out practice. Participants 1 and 2 said in the same context:

"I mean 3D printing, you can rapidly print out and see… I think what I learnt the most is trying and failing and redoing" (Participant 2, end interview)

"It's creative, it's a process, whatever happens, happens, if there is any problem just print it, see how it works and then you do it if you want" (Participant 1, end interview)

And an almost identical idea from participant 4 while elaborating on how 3D printing can be useful:

"You can design it, print it out, check it, see what works, maybe learn some other problems that you hadn't seen in the software. So, 3D printing is really nice for just that prototyping. And then you can go on to creating it in different materials." (Participant 4, end interview)

Testing out from a CAD problem can also relates to the achievement of a better understanding on the size of things. Even if you use tools to bring your design on a 1:1 scale, having it in front of you, gives a much more clear and robust idea of the size of it. Participant 7 brought up this thought during the interview, commenting on how one might have a subtle idea on how the object shall look like in real life from the design or even by using tools as a ruler for example. There is much more of a difference though when you actually have printed the object and then you can see the size or even see possible issues. 3D printing mediated knowledge for him concerns mostly having a clear idea on the reality and size of the things one wants to print. As he stated:

P.7: "I think sometimes helps you have an idea about the size of things? Because sometimes when you have something on the computer screen you gonna be like… It's gonna be this big…but when you actually have it…printed out… I guess that's how it would actually look in real life. I mean you can always take a ruler and say…that's gonna be like 25 cm or that would be like this (showing with hands…But actually having the part then you also picture out if there is like any issues with the physical part…" (Participant 7, end interview)

His teammate, Participant 10 was the one who actually brought up an example from their own printing experience, when they printed a leg which they thought had the right size, but in the end, it resulted to be huge for what they wanted to make. She emphasized on how having even the more accurate measurement on screen there is no comparison with having the real object.

P. 10: "Yea. Like we start with designing the leg and when we printed it we realized it was really tall (laughs), the spider would be like huuge. But you don't have a feeling of the size of it on the screen, even if you have a millimeter measurement of things, it's not the same." (Participant 10, end interview)

Another important point is how with 3D printing one can create a product of imagination without having to buy almost anything; 3D printing means rapid prototyping which means that you can get have what you wish to print and use rapidly. This discussion is mentioned not because of matters of financial accessibility. It was brought up by most of the students as a factor that is motivating as you see rapidly your results and creativity as you can create at any point parts that you find out you will need. The participant 5 insisted especially on that fact, describing how one can make all kind of different things without having to wait for any of it, more than the printing time:

"Making something…without having to buy some parts. Just make all the different stuff… You don't have to buy things, you don't have to wait for things, you don't have to find out which of these parts are needed and that's a very positive thing about 3D printing… that you should probably always be able to make the most of the things you need in 3D printing" (Participant 5, end interview)

Participant 9 then came up with an example from their own printing experience, when in his team they needed an attachment point to a stirring device. In the beginning, they were searching for thing they could use to attach the robot to the device, but in the end, they realized they could just print something and that is what they actually did really fast:

"One example, we have this motor…it doesn't have any attachment point, so we thought about… What can we use to attach it? Well, we can just 3D print something and we did it…We just sketched it up in a couple of minutes…" (Participant 9, end interview)

Later on, during the same interview participants made another reference on how the rapidity of results of 3D printing can be highly motivating, as they had the 3D printers in the lab available at all times to "just make" whatever they would need for their project:

"…that we actually could 3D print at all points, if we ever need something is at most 18 hours away. That was very motivating because everything you need…you just go and make it." (Participant 5, end interview)

"The rapid part was motivating…it was always like we can always go and print this." (Participant 9, end interview)

Participant 3 expressed the same idea when he is explaining how the rapid prototyping was motivating for him. He went further though, in comparing on why this rapid incentive is motivating compared to other electronics courses where one can see the results of projects only by the end of it.

On the contrary 3D printing, he says, offers immediate interaction, making it good tool which offers independence from market products:

> *"…So that compared to the actual electronics that I have done, you can work for a few months and of course at the end you have a proper working thing, but during the working hours… you are just working and you cannot really see…any physical progress. So that's really nice…I think it is a good tool…It's a process where you don't have to depend on other companies or anything else but you just go up to the lab and do it yourself." (Participant 3, end interview).*

Participants 1 and 2 also commented thoroughly how they find 3D printing useful in many more aspects of the working and everyday life, adding values to rapidity such as the low cost. Participant 1 characteristically said that in his department if they need an antenna or a detector etc., "*they can just have it printed*" and participant 2 illustrated the fact as "*exciting*".

Participant 7 was also explaining how 3D printing could be very much useful in everyday life by suggesting a possible use of it at his work project. On his suggestion, one might focus on how he comments on 3D printing giving incentives for thinking on everyday applications. As he says it is a tool and one can explore several ways of using it: "*It made me think of other opportunities. As I said another tool in the toolbox!" (Participant 7, end interview)*

During the interviews, there were also small comments on another knowledge practice, on **simulation** and how it helped or not during the 3D printing process. Simulation is closely connected to visualization of the object. Here the 3D printing designing software was used as a secondary artifact were the students had to represent the object to make and sometimes as a tertiary artifact when one has to think ahead on the design, creating ideas for the next steps. For example, when participant 4 was asked if 3D printing allowed for any development of knowledge, he answered that software simulation might be a complicated process and sometimes it would be just easier to print and see the result:

> *"You get to experience unforeseen things. [on printing]. You get the experience of "Yes I actually have to account for this". But if we were to simulate, that would be a lot more work…" (Participant 4, end interview)*

Participant 2 refers to how simulation was mediated from designing allowing for visualization of the product and shape exploration. He focuses on how by seeing the simulation he could have a better image of the whole and then break it down to shapes:

> *"I mean I realize one thing. With the 3D program, it is much easier to see an object and then realize how we can divide it and make the same object like in real life…yes we learnt a lot." (Participant2, end interview)*

During the interview participants 5 and 9 also had a conversation on how the motion simulation helped them realize problems with the walking pattern. They spider they made would actually move only the knees and would not walk as it had to. This is something they realized just by the time they were simulating:

> *"But that's the interesting part…that we didn't catch at first but when we tried to simulate it we saw that oh…it would just move its knees…we didn't think it through, and he had to spend hours doing it again…Yes. It was good to simulate stuff." (Participant 5, end interview)*

One of the last levels in the creation of a robot is the **assembling** the various parts of the robot. This is a knowledge practice something that usually follows the printing process, especially if one uses the regular 3D printers which cannot print two blended parts together. This is a process the students of this course also followed: *"… and then you have to assemble the whole thing and look at the walking pattern…" (Professor, initial interview).* The assembling experience mediates information on the 3D printed parts in several ways and leads from the bits to one whole and final product. It is mostly an implicit mediation which happens through these secondary artifacts: The final product represents the desired and imagined objects and it's only then that some students acquire knowledge on the object, that they were previously acknowledging.

A group used rubber bands after printing some parts as muscles to keep some edges connected. Participant 5 from the group explains how it is different to assemble the robot in rea life and not in a stimulation, as you can feel the forces, while in the software they could apply use gravity. On this try-out one the participants commented on how by assembling mediated information on the movement of the robot:

> *"If you put these pieces of rubber string around the joint and see when it does actually start to need more effort to move and when it becomes easier, that's hard to do on the software. It is just going to move linearly or with gravity. But we wanted to see what actually happens…" (Participant 5, end interview)*

Another student from another group realized during assembling that the PLA (the printed plastic material) was not strong enough in order to hold and move with steel line. As a result, he had to change it to fishing line in order to make it work, so he comments:

> *"Yes but it was steel thread…it's quite strong… when I started pulling and bending the material it snapped quite easily…but since it is metal of some short it gets some intense in the*

thread and I think that's why it breaks compared to the fishing line, which is really strong…" (Participant 3, end interview)

Participant 4 also detected moving problems after assembling the printed parts. He didn't realize that the knee of the robot was bending too much until he started programming. Then as followed during the observations ha had to design it differently. As he said:

"After I assembled the whole robot and then began programing it. Then I noticed that it flexes too much" (Participant 4, end interview)

Printers as primary artifacts sometimes need too much time to print bigger things or they don`t provide space for those, or they cannot print them due to shape anomalies. Then the operator shall find creative ways to divide the shape in such ways that the printer can actually print and then reassemble these together. It is always interesting to see how a simple printed object can represent different thinking and creative tasks. Hence assembling can also be the result of printing deficiencies. The participant 10 stated further that 3D printing sometimes requires assembling due to technical restrains in size for example:

"For instance, some parts are impossible to print them, so you can just divide them into two parts and then screw them together or glue them together and solve it short in that way" (Participant 10, end interview)

For Participant 3 assembling brought up a problem connected to materials and printing modes so that he had to try and manipulate the final product. Actually, he did not take under consideration the support material that would fill a whole in the leg of his design, so he tried to drill it out. However, this did not work and he had to try multiple times within the assembling process to finally print the one that would fit the initial design:

"Well I tried but it didn't work at all so… (laughs). So, I abandoned that one and print again…And I had both the thigh and the calf and I have to print both of them like four five times just to get them correct." (Participant 3, end interview)

As he mentions these are problems you usually get from the cheaper printers, which are the ones usually used in classrooms. He later on used another kind of printer also available to the students with water dissolving support material (Observation sessions).

Assembling is an important procedure which represents challenges from the printing process as well as creative changes and solutions that have happened in order to achieve it. Someone might suggest that assembling is not a part of the 3D printing process but a separate autonomous procedure. The above quotes were used to show how this stage of modelling is closely connected to 3D printing and meditates knowledge in different ways.

In sum, it is intriguing how many knowledge practices can be represented just in one process such as 3D printing. As the interviews show 3D printing allows for designing, testing out, simulation and printing with an interconnectedness flowing from one to another. In this section, we have seen that students enacted a set of knowledge practices during the 3D printing process. The swifts between identifying design challenges and errors, exploring solutions and testing these out by printing were important in the process. This gives a more deepening image of Johri's ideas on how learning can be connected to technologies through allowing for *the shifts in assemblages by leveraging different affordances*[5] *of the material and even of the social* (Johri, 2011; Hutchins 1999; Pea 1993a; Norman 1991). These shifts can be the different knowledge practices analyzed in the chapter. Below there is a board with the main knowledge practices presented.

Table 2 The main knowledge practices that are involved in the 3D printing process

Design	Testing out and printing	Simulation and visualization	Assembling

5.3.2 How 3D printing provides experiences with different materials and knowledge forms

The focus of this section concerns knowledge forms that emerged during the interviews. These are thoroughly connected to the socio-material perspective and to how through the tactile experience, the printed object becomes a tool that represents the different assemblages and relates to the externalization of the ideas. There is an emphasis by the students, which becomes obvious in this section, on touching and seeing the objects in real life, on the tactile experience connected to the basis of materiality. This way of interaction offers specific opportunities for experiencing the world and exploring the different materials. As the professor opined: *"I use to say that the printed object says more than words and pictures"* (Professor, initial interview)

Most of the participants did not seem confident on why having a real object in their hands could be different but they all agreed that it did make a difference. Not being conscious on how the printed

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[5] Affordances: Different social and material aspects of the assemblages.

object mediated knowledge is another reference to implicit mediation. Participant 1 when he was asked about learning from the 3D printing experience got confused in the beginning, repeating the question with surprise and then his first answer came to be on his tactile experience:

> *"I learnt a lot about what you have in your head and then actually making it and having it in your hand was cool…It's easier to visualize stuff now." (Participant 1, end interview)*

The engagement of other feelings, except of the vision is important for the students and make the course more attractive. His teammate following up the conversation mentioned that with the real object one would have the opportunity to feel it and understand the precision of it:

> *"… draw in the CAD…but you don't know how it will feel, how precise will it be?" (Participant 2, end interview)*

When asked on the course, students again kept bringing up the "practical" experience that made it differ from other courses they had in the past, and how this one was better in this way. When participants 1 and 2 were asked on what would be different in this course if 3D printing was not included, they elaborated a conversation where they commented on how the course would be the same with all the others, just with theories that after a while one ends up forgetting, with no material work, no implementation:

> *"P.1: It would be like all the other courses. No practical experience, no hands on.*
> *P.2:…That's actually the issue in most of the courses in this university. A lot of courses have a lot of CAD, a lot of physics, but you don't…*
> *P.1:Only theories. Only theories. And we never use anything…*
> *P.2:We never use anything, we don't get to implement.*
> *P.1:And then you forget it, because you have to fill up a new course" (Participants 1 and 2, end interview)*

While explaining how 3D printing was motivating for her to work on the project, participant 10 also mentioned the materiality aspect. For her, being in the physics department, most of working and studying was taking place on the computer. With 3D printing, she got to engage in more practical work while she also started thinking differently:

> *"I like having something more practical to do. I mean it's a lot of work on the computer but it's still a more practical aspect of it instead of what I am used to. Which is a very different way of thinking…it's good to have some more hands-on work to do!" (Participant 10, end interview)*

In the beginning of the interview participants 5 and 9 were asked why they chose the specific course. They expressed similar ideas with participants 1 and 2. The course would be fun and it would incorporate not only mathematics, but also the result of it, the actual object which, he comments, is especially motivating:

> *"I personally chose it because it looked like fun and it's really a practical course so we make things, we don't just do calculations and simulations. We are actually able to see what we are doing…so that's my motivation" (Participant 9, end interview)*

His teammate participant 5 agrees, but he uses a vocabulary which shows stronger connections to the tactile learning, by using the verbs touch and do and contrasting it to "doing math" which implies a theoretical activity:

> *"…Basically, it is something to touch and do instead of just doing some math, lab script and moving on…learning something, while seeing the results of what you did." (Participant 5, end interview)*

By the end of the interview both students were asked if they would like to add anything and they brought up again the subject of materiality and how it made the course different compared to others, and how it was *"motivational…to make something and create"* (Participant 9, end interview).

The connection of motivation with the material aspect of the course was common between the participants. Motivation is an important parameter of constructing knowledge and facilitates it. Participant 4 explained how different apparatuses of the 3D printing family such as CNC or laser cutting machines would make no difference concerning the motivation as long as something was to be created.

> *"Yes, but the motivation would be the same as long as we get to create something in the real world and not just a file…so even if you have the laser printer I think the motivation would be the same." (Participant 4, end interview)*

Another important aspect of the printed object in the context of the socio-material perspective is how it overcomes its material nature and becomes an object where you can easily locate any building malfunctions in your own process. The 3D printed physical version offers a better understanding of the object and represents also software knowledge. This means that the same object can give incentives for further exploration of the software. Participant 9 expressed this very idea:

> *"… But it made it much easier to hold it and try it… I learnt also that 3D printing it and holding it, it's a lot easier to see actually how it could work, rather than simulating it and making it on the computer, and it goes both ways. So, when I design something on Solidworks and print it then I also learn something about Solidworks." (Participant 9, end interview)*

Printing an object is not only about holding it. You bring your idea to the world. Arguably this is a socio-material aspect related to the concepts of artifacts, the secondary ones, which represent ideas.

Bringing an idea to the real world represents a whole chain of practices; Students have explored materials, have faced various challenges and tried out many different ways of doing things in order to achieve that. Participant 9 tries to explain how this experience is important for him:

> *"It is fun to make things and then hold the results and everything. But also taking the idea out in the world…it's really positive I think and really good." (Participant 9, end interview)*

In a parallel way, this idea also expressed by the participant 7 who described how engaging was to put all things together in order to create something real, especially when you have started from literally nothing:

> *"…you can actually make something physical and put it together, it's very interesting, cool… that you can create that out of nothing" (Participant 7, end interview)*

During the observations, participant 10 was quite excited with the printing process. When she was asked on how she experienced 3D printing, she confirmed the facts but she also elaborated on this idea of bringing your idea to the world. On how the idea becomes real and this can be the source of much excitement:

> *"Yes, it's also very exciting. I remember the first part we made…we designed it and we print it and it became reaaal. I was like super excited." (Participant 10, end interview)*

Her teammate, participant 7 communicated the same thought, when asked on the usefulness of 3D printing and he commented further on how this procedure of bringing an object to life can facilitate the understanding of the object and how one can speak about it to others. Nevertheless, his understanding of it is also implicit as he couldn't put in words how having a real object can affect ones' understanding.

> *"You can make something real! And that's sometimes much easier to explain to someone…how it would actually work…when you can see it real whereas you can just show a picture or something… they would be like ok yea… But if they have it in front of them it's much easier to…give a different type of feedback…" (Participant 7, end interview)*

Summing up, the data in this section shows that the perception of learning by the students as well as the usefulness of 3D printing is closely connected to materiality and especially the tactile experience. This sets a reminder on how the socio-material perspective *'assists us in providing interpretive explanations of learning practices that account for technology contextually'* (Johri, 2011: 215). Students actually insisted on how the printed object can assist in different way of thinking, understanding and even explaining the world. This is how the objects/materials overcome their meaning to become learning resources. (Johri, 2011).

5.3.3 Technological affordances and restraints of the 3D printing that matter for learning

3D printing as a tool and a process allows for different technological affordances that facilitate or restrain the construction of knowledge. These were mentioned a lot by the students mostly around topics on challenges and problems. Technological affordances and restrains as explained by Johri (see section 3.3.2 in the Theory chapter) are of interest in this study, because they can depict what kind of possibilities can offer specific technological characteristics for knowledge mediation.

However, any technological restrains that will be mentioned should not be considered as a significant obstacle. Technology changes fast and in most of the cases covers technical defaults from one version of an apparatus to the other. In a similar way 3D printer becomes also simpler, demanding less and less knowledge on how to use it in order to do so. As a result, working with such apparatuses relates more to how one learns to be adaptive, then learning perfectly how to use one single machine. 3D printing represents this kind of adaptive knowledge. This was a point mentioned by the professor of the course:

> *"With technology things are always so fast …so things they need to know about the 3D printer, about how to use it, how to maintain the 3D printer right now can be obsolete next year. Because they have different printers next year. So that's a difficult part, but on another way, you are learning to learn…it's about relative knowledge, because things are evolving so fast…. That's called fluid knowledge I guess…" (Professor, initial interview)*

One important learning aspect that 3D printing affords, is that different printers account for different printing characteristics although they can all print the same basic stuff. For example, participant 3 had a tiny hole in his design for which he had to find a way to print it without support material, or a way to remove it after all. As a result, he decided to use Ultimaker 3, which offers water resoluble support material. This was also hard to remove but at least possible:

> *"I actually used the Ultimaker 3. But I did learn something for example the water resolved material. Actually, it is not that easy to remove. At least when I had this tiny hole." (Participant 3, end interview)*

On the other hand, participants 5 and 9 chose to use the Objet printer which offers more precision for small details and their spider had many small holes on the design. Participant 9 mentioned during the interview that "*the Objet is also more precise so you can print smaller holes. And our robot has pretty small…that's the actual reason why we used the other one*."

One technological constraint mentioned by almost all students is how the most used (and simple) printers were clogging all the time. This means that the material would be stack and the printer would not print. This was caused mostly because or wrong settings or the material. Participant 4 commented on this during the interview: *"definitely lots of problems with the 3D printers stopping working because it's clogging up and this again is because of the plastic and the settings on the parts"* Students came to realize that they should change the printing setting to resolve problems like this by the end of the project by searching online.

An arguably interesting affordance concerns material exploration. As 3D printers can for a variety of materials one shall explore them or test them in order to find out which is the adequate one for a certain design. Some materials might be more flexible while others more robust. Participant 9 characteristically said that *"there are stiff materials and flexible materials…And then you can choose not to be flexible".* During the same interview participant 5 commented on how the use of the Objet printer offered him the possibility to explore a new material that he had never used before, which can be transparent and does not make it obvious that it was 3D printed:

> *"Also, that the materials that were printed by the Objet were so different because I had only 3D printed materials I knew of…But Object just gives you an object that can be c-thru and just looks fantastic." (Participant 5, end interview)*

Participants 1 and 2 also chose another printer, opting for flexibility for their runner's legs, as the PLA printed by the simple printers has too much *"sharp edges which makes it easier to brake" (participant 2, end interview).* Later on, he also commented on how the same printers are very good for prototyping, but they don't offer strong products, *"not high quality".* Participant 7 made similar comments during the end interview saying also that *"it doesn't have that short of feeling that it is a solid, robust piece*".

The Solidworks software also represent certain technological affordances. As a complex CAD program, one shall use it for a long time in order to master it. Hence, it allows for new discoveries all the time. As participant 5 said during the end interview: *"You find still new things in Solidworks that you don't know of, that you should do, like the relationships".* The same participant commented on how difficult it is to learn the software so well that there is no need to start over again at some point:

> *"But we know that at some point, in some perfect world you should be able to design something that you can just start, open and then make a new part that fits on." (Participant 5, end interview)*

Participant 10 gave a similar example, describing how she wanted to design some parts but it was to complex, so she discovered a toolbox in Solidworks which was offering ready made parts that one could modify. However, as she noted, that was tricky as well given that she had to find out then how to save the modifications:

> *"Well first I tried to design the gears myself…are apparently way more complex…But we found this toolbox with several premade parts we could use and modify but it was…We haven't learnt about it in the lectures and it was trickier than I expected." (Participant 10, end interview)*

To summarize, technological affordances and restraints of 3D printing were presented as commented by the students. This are elements that are represented by the 3D printing process and the 3D printed object and mediate themselves several opportunities for knowledge exploration. Below there is a board that depicts a summary of these.

Affordances	Restraints
-different materials to choose	-clogging of the printer
-rapid results	-cheap printers-less precision
-many possibilities given by the CAD program	-difficulties on taking off support material

Table 3 Technological affordances and restrains related to knowledge construction

5.3.4 Pedagogical challenges and dilemmas

This section is closely related to the second research question on challenges. This course brings together so many knowledge practices to students from different educational backgrounds and as a result it has quite some challenges to deal with. Below, these challenges and dilemmas will be analyzed as presented by the students and the professor during the interviews. These are of special importance for the research questions, given that they shed light on limits and settings for knowledge construction.

The first challenge for the professor himself was to organize all different learning practices and knowledge content in ways that it would support student learning. In other words, to combine all the various mental and physical artifacts in order to produce knowledge mediation within the process of 3D printing. There is actually no other course that has done this before so there was no guide on how to set it. Usually other existing courses focus in one only area of the process such as designing or programming. However, it apparently worked well and students get to engage to the different learning practices as much as they need in order to use and combine them. The professor elaborated further:

> *"I don't think that there are other courses in the world that are similar to this, because it's a very wide course…they are learning different things and different theories…I was quite uncertain at the first time if it was possible to do that…But it works quite good so…It's because other courses typically focus in one of the areas, and go very very deep in one…all these different topics, I think they are belonging together and it worked quite good also. So…we are going just deep enough to be able to use them together… that's the goal of the course." (Professor, initial interview)*

Another main challenge of the 3D printing course was that the students were quite different in the sense that they have previous educational and 3D printing experience and thus they require different support. During the interviews, the students answered some background questions which provided the relevant information. For example, participant 3 has studied electronics, participant 1 electrical engineering and microelectronics and participant 10 space physics. Furthermore, they have differences in their 3D printing experience. Hence, Participant 9 had some previous 3D printing experience but with different CAD programs, participants 3 and 7 had no previous experience at all and others like participants 2 and 4 answered that they had some CAD experience with other programs but no experience with 3D printing. It is arguable that with such differentiated experiences, there is created a pedagogical challenge on how to support these students during their learning experience. Themselves they expressed quite different opinions on their learning needs. For example, participant 10 was very satisfied with the group sessions-lectures where students would work with the professor to design things:

> *"I kind of like how the course is build up with the lectures and then these short of group sessions where he does some exercises on the board or the projector and we do it simultaneously in our computer which I think was really really helpful. That's definitely what I learnt the most from." (Participant 10, end interview)*

On the other hand, participant 5 suggested that they design and print something with the professor before starting with their own work, while his teammate disagrees, given that this would restrain their freedom.

> *P.5: "Making something that works with him first? And then make something on our own."*
>
> *P.9: "I wouldn't say that because as I said I liked the freedom that we get" (Participants 9 and 5, end interview)*

More participants had many malfunctions with the 3D printers and asked for more technical information on how the printers work and how to fix those malfunctions. Participant 4 as an example, asked for more information concerning the software for the 3D printers due to many technical problems during the course:

> *"better introduction to the Cura. Because yes. There have been some problems with printing and I think that would be solved by getting a better introduction to Cura." (Participant 4, end interview)*

Having all these different backgrounds to learn all the different knowledge practices, one might have to move out of the engineering or robotics world to important learning incentives such as creativity that can stimulate new ways of thinking. Under the challenge of differentiation, the professor chose to be open, taking under consideration the different experiences students have and highlighting the creative part of the process as it is already discussed during the course setup description. He underlines the importance of learning how to think in other non-conventional ways through the 3D printing process which can be meaningful later on in student's lives:

> *"And if you can show you can do that in an open-minded way that's, that's the best for me actually. But of course, there are different sublevels; If you are very engineering like, and a very good engineer can make things at a low-level work that's also good but I appreciate the more high-level creativity, and if a student can learn to open up new ways of thinking in this course and take it with them, in their lives…" (Professor, end interview)*

The dilemma of freedom is another question to be tackled. This concerns especially matters between learning support during the course and independency. It also concerns what part of the projects is pre-decided or not during the course. Participant 5 who had already discussed this idea of freedom earlier in the interview, explained further that students need to take initiative and responsibility but still, this is something that depends on the person. In his opinion, most students adapt well in this environment of freedom:

> *"you have to take initiative on the individual level, so it's a lot up to the student and we work well within that. It depends on how people want it. I think we are very well suited to this sort of learning environment. As long as you take responsibility for yourself that's ok." (Participant 5, end interview)*

The Professor agrees also that students shall be "open and dynamic…creative and freer" As he mentioned he focus more on the process than the product itself which distances the process quite a lot form real-life engineering and emphasizes on its possibilities for learning exploration: "The design process itself is quite nice I think…it's more satisfying for me to stimulate the creative part"

Challenges related to students' background knowledge and need for support	Challenges related to the new student role	Challenges related to knowledge content
• Different backgrounds of the students • Different students' opinions on teaching support	• Students have to be responsible for their learning • Students have to be open to creativity	• Different subjects combined to be learnt • More technical information needed • Understanding the affordances of the technology

Table 4 Pedagogical challenges when working with 3D printing

Above there is a summary depiction of the pedagogical challenges. Challenges and dilemmas are significant as they set parameters such as constrains in learning choices or ways of teaching that allow for an inclusive curriculum. The freedom that students can enjoy during a process is also connected to their ability of taking initiatives. In addition, an inclusive way of teaching is connected to teaching methods that are more focused on skills everyone can elaborate, such as creativity. All the above create a learning environment where knowledge is being mediated through many and different knowledge practices and by using a variety of artifacts and tools.

5.4 Summary

Summing up, in this chapter, the data analysis was presented in four different sections about knowledge practices, materiality and tactile forms of learning, technological affordances and pedagogical challenges. It is considered important to have in mind that interviews are the main data source which allows us to conclude that all the descriptions by the participants on the 3D printing process show also their personal perceptions on the subject. The interviews provide an insight of the personal experience of the participants from their knowledge construction experience.

Recapitalizing, 3D printing is perceived as a useful artifact in the learning process both by students and the professor. From all the interview data, supported by the observations it can be argued that the 3D printing process can be motivating, can stimulate creativity and boost the imagination, but also make people think in different ways than they are used to and learn how to learn from their own mistakes. Some of the participants expressed opinions also on how 3D printing can be useful out of the learning context, within the working or everyday life. A quite representative answer is that of

	Design	Testing out and Printing	Simulation and Vizualisation	Assembling
Motivation and creativity	provides the designer with an artistic point of view and a better perception of geometry	motivating process also due to rapid production		incentive for more creative solutions
	thinking in different ways than usually			
Materiality and shapes	explore patterns and shapes	shape exploration	shape exploration	facilitates the exploration of different ways to assemble, depending on printing features
		material exploration		material exploration
		feel the object		feel the forces in real life
		provides the possibility to see the actual/ physical progress		
Facilitating visualization	visualize the next steps on one's mind	easier to visualize	easier to visualize by simulating	Easier to visualize
Fixing Mistakes and Trying again	learn how to start simple	learn to find existing mistakes and fix them in the design	learn to find existing mistakes and fix them in the design	learn to find existing mistakes and fix them in the design
	learn how to design and redesign		facilitates the perception of the design as a whole	check the pairing of the different parts
	learn how to start over to fix mistakes			
	perceive all the details of a design by fixing mistakes			
Other applications	useful in other master or PhD tasks	low cost applications in work		

Table 5 The different knowledge practices and the learning opportunities

participants 1, 2. When they were asked during the interview if 3D printing was related to their engagement to the project, they both said multiple "yes" with lots of excitement and then participant 1 added: "*Mondays, Tuesdays are the best days. The other days are labs and courses….*[6]".

[6] Mondays and Tuesdays were the days when the course took place

Eventually, as the data confirms 3D printing is considered useful both by the professor and the students. Some may not see it as an everyday device that would use in the future, but all of them perceive it as an apparatus that provides motivation and stimulates the creative mind during knowledge exploration.

Above (Table 5) there is a table that summarizes the different knowledge practices as they were presented earlier in this chapter and how the interviewees considered these useful mostly in learning. The table aims to simplify and depict the descriptive presentation of the analysis. For that, there is a grouping of the different features mentioned by the students. The horizontal categories denote the different knowledge practices that have been identified in the analysis of the learning activity, and the categories in the left column summarizes the ways in which the work with the 3D printers provide opportunities for learning in relation to the knowledge practices. Furthermore, through this table, a point made earlier in the analysis becomes more apparent, that the knowledge practices were recurrent in the design process and that the way students move in and between them in their work affects how the learning opportunities are realized.

6 Discussion

In this chapter, the findings will be summarized in a way that connects these to the research questions and discuss how these findings support and differ from what is found in the previous research discussed in chapter 2. The chapter will also discuss how the theoretical resources provided on chapter 3 can help us understand the findings.

6.1 The knowledge construction practices

This section, will discuss the ways in which knowledge practices, as found by the data analysis, in the 3D printing activity are connected to the different roles of artifacts, as elaborated by Wartofsky (1973) to show how knowledge construction happens within the 3D printing process.

The findings of the data analysis give support to the five different knowledge practices through which knowledge is being mediated and constructed. These knowledges practices answer back to the ways 3D printing as a tool and a process provides students with opportunities for exploration and knowledge creation. First of all, it is significant to understand how the various artifacts and tools that are mobilized in the knowledge practice can take multiple artifact roles and how all knowledge practices in this project were interconnected.

The first knowledge practice that happens when the 3D printing process starts is designing. Students have to conceive an idea, elaborate it on their minds, pre-draw and design to reach visualization. These resemble to the design stages as presented by Maier et. Al (2014) which are to capture ideas, to get insights, to complete a design of a product (here: the pre-drawing), to elaborate this design, to manage the design process or find out the consequences of the solution the design is aiming to. The data analysis supports these stages, but in the present study they took the forms of conceiving an idea, testing out, design and simulating. These correspond respectively to capturing ideas, manage the design process and find the consequences, complete the design and visualizing. The different terms used in this study do not imply significant differences in the design stages, but were selected because they were more often defined like this by the interviewed students. In total, the findings of this study give support to Maiers' description of the phases, but the present analysis reveals in addition the importance of testing and suggests that this should be recognized as a separate phase or activity in design processes which is important for students' learning.

In the beginning of designing, students create an idea on their minds on how their robot shall be. At this stage, the imaginary design functions as a tertiary artifact when the students have to imagine their robot in the making. Then the pre-drawing and the design in software take the role of secondary artifacts which actually represent the object to be made. These two artifact functions mediate knowledge as the data shows in a way that students explore their own thoughts and ideas, learn on the affordances of the software by using it and as some of them admitted along with the teacher, they become more creative and they learn to think in different ways. Nevertheless, design stages have no clear boundaries, so by designing, students might step back to imagine the shapes and design again which results to continuous changes from one artifact role to another. The fact that some artifacts may take several functions in the process contribute to drive the process forward.

From that secondary function of designing students get to reach visualization. This means that they get to see a 3D version of their ideas and even simulate motion. This is a process where knowledge is mediated because as the participants said they have the opportunity to explore their designs, realize any possible malfunctions and find out all different ways to correct them.

Two other knowledge practices are interconnected with designing; printing and assembling. While assembling allows for a similar knowledge mediation as the design, in the sense that offers opportunities to locate and fix mistakes, together with printing, they offer a unique experience on which students emphasized a lot; the tactile experience. In this case emerges the necessity to account for the material world around us from which we extract and construct knowledge. It is also important to mention how printing can opt for the visualization in real world, and as Kanev et al. (2012) highlights, being able to see and feel is important for understanding and learning. It is relevant here to emphasize on how the participants focused not only on the tactile experience with the printed object, but further on the way their ideas came to real life and how this differs from the virtual world.

Last but not least, the 3D printing process in its whole opted for testing out all kind of different artifacts in all different stages; ideas, materials, software functions, different printers and designs. By testing out knowledge was mediated, as the students had to consider all the different parameters of the artifact to test and change according to their ascertainments. To test out means to explore possibilities and make the best choices. And by exploring possibilities one gets to construct knowledge on these.

To understand further how resources were used and mobilized in the process, one may turn to Johri (Johri, 2011) and his notion of learning as it happens when students shift between the different material and social aspects of the assemblages; in other words, the different resources students might use, in order to construct their knowledge. In chapter 5 different assemblages were presented such as materials and apparatuses, but these were not the only ones students came to use during their project. The various knowledge resources and tools were assembled during the whole process along with several tools, some of them mentioned already, such us rubber bands, screws, drillers, screwdrivers in order to combine knowledge forms, perform knowledge practices and produce the final robot. With this example, one might understand further this shift between the assemblages.

It is also important to explain how mediation happens both implicitly and explicitly during 3D printing. One has to understand mediation in order to understand the process and the learning potentials of 3D printing. As it is explained in chapter 3, according to Wertsch (2007) explicit mediation consists in the mediation that is triggered by external factors that might be signs, people or objects and happens purposely and consciously. For example, students during the interviews started by mentioning useful aspects of 3D printing as a primary artifact. In other words, the first idea students could come with in matters of usefulness, was that of a designing or a constructing tool; an artifact that allows people to produce something visual or tangible. This is an incentive of explicit mediation. On the other hand, the term implicit refers to the internal mediation which usually takes place in an unconscious form. During the knowledge practices, it is easy to understand how different external and conscious factors lead to explicit mediation. Nevertheless, it is significant to understand that implicit mediation also happened as the data showed. Many students, when asked if they had learnt something during the designing or printing process they initially answered no, while later on they came up with all kinds of various ideas on the knowledge they had acquired. At that point, the knowledge which was implicitly mediated, was externalized in a conscious form. By elaborating how implicit and explicit mediation happens, one can have a deeper insight into the ways knowledge construction can takes place within the 3D printing process, given that it does not only happen in externalized forms.

Another analytical tool that was used earlier is that of representation. It has been said throughout the data analysis that the process is represented in the object or that the object represents all the knowledge practices. It has been explained in the theory chapter what representation is and how it is connected to 3D printing. What one shall add at this point is a very specific connection of representation to the material object. What the data analysis offered in addition, is students' opinions on how the 3D printed object is; how their idea is represented in the material world. Many of the students expressed that very idea, that by 3D printing you bring your idea out to the world and this equals that the printed object itself represents not only the knowledge process but the idea itself and thus how this idea came to acquire a material form of being and not only a mental one.

To sum up, until this point we took an intrinsic look on how the findings from the interviews and the participant observation that were presented, elaborated and stirred by the theoretical context answer on opportunities for knowledge construction according to the participants' perceptions. Now, the researcher will continue further with showing how the concept bricolage can be fruitful for this research.

6.2 Knowledge construction with technological artifacts- from tools to the bricolage

At this point it considered important to introduce a discussion on how all these data can be seen through the lens of bricolage. Bricolage is a concept that will be explained as lens to understand how knowledge creation works within 3D printing processes, given a socio-material base.

During the observations and the interviews, it was made obvious that the knowledge exploration happening during the 3D printing process is not purely about mediated knowledge but further than that, it is an active way to understand the world around us and use all the different resources provided. The concept of tool-mediated action cannot fully describe or explain this aspect of the design process and 3D printing activity, where both are being framed by the available resources. Another way to understand and explain further this kind of knowledge construction is through the concept of bricolage.

Bricolage is a relevant concept to understand how the 3D printer functions as an artifact in the same challenging way that the bricolage does when applied in learning environments. Hence, this is a socio-material concept that can go further on showing how learning is viewed in the context of this specific theory. The socio-material bricolage, first introduced by Levi Strauss in 1967, is a theoretical concept which will be used in this study to explore the application of the socio-material perspective in learning. For Levi Strauss, the bricolage is a tool for exploring how sociality and materiality are braided in the human activity. He actually seeks to define what people can achieve with what they have in availability and not by planning and pre-requiring specific tools (Levi Strauss, 1967). In the case of learning technologies, the bricolage can interpret the link between planned and spontaneous practice (Johri, 2011). In the course of interest, the students are provided as well with a predefined variety of materials to complete their tasks using 3D printers, mainly due to cost implications. Furthermore, the process of 3D printing is a constantly readapting procedure to technical and material implications that come up during the construction of an object. As such the concept of bricolage, in the sense of unplanned resourcing is a concept that can interpret the process in a challenging and interesting way.

Going further into the material aspect of learning using the theory of bricolage, it is important to note that one creates knowledge by using the material and social resources he already has in availability (Orr, 1996). Arguably, by using a 3D printer, the students shall realize their projects using specific software and hardware. As stated in the course description: *"Only a limited range of materials are available – mostly polymer/plastic, metal such as titan has just arrived"* (Course blog, 3/5/2016). Accordingly, students in this course are working in line with the socio-material bricolage, as they have specific resources available and they have to find the best ways to get to know and use them. In the epistemology of the learning technologies, focusing on the material aspect has the advantage to provide a hermeneutic context for socio-cognitive awareness, equally material and social and open to any forthcoming distinctive elements of assemblages[7] (Johri, 2013).

Bricolage as a concept offers a very specific perspective to look at 3D printing; bricolage braids the social and the material by offering a given number of affordances in a knowledge constructing environment, in order to achieve a final aim. This is exactly how 3D printing works. It gives the freedom to imagine almost anything and print it but it creates its own bricolage world by offering very specific ways for printing and a given set of tools. This means that you start from the idea and then you have to give your idea a form that is in line with the different material and printing restrains. Then from the material aspect you get a continuous interaction of the material and the social through the knowledge practices as these were discussed earlier. For example, when students commented on material restrains or printer restrains that lead to choices within the 3 kinds of printers and materials they had available, this is bricolage. Then these choices on the material led to social in a way that students had to represent their initial ideas in very specific ways in order to be able to print them and this as a whole included a variety of mental processes. Then again you get the printed object and along with that, this emphasis students gave to materiality and the tactile experience which allows for the social to tangle itself around the material and offer one final knowledge construction experience.

[7] Assemblage: technology as a tool in socio-cognitive context (Johri, 2013).

To sum up, the concepts of bricolage was elaborated further in this section to show how they can provide the reader with a deeper understanding of knowledge construction through the 3D printing process.

6.3 Challenges and opportunities for learning

During the course both students and professor had to cope with different challenges which were pedagogical but also technical. In order to come up with solutions, the participants had to be creative and sometimes think in different ways than they are used to. Unfortunately, not many researchers have deepened into the challenges of 3D printing, especially the pedagogical ones.

First of all, the pedagogical challenges consisted in two parts in the data analysis; one that concerns the different knowledge material that has to be combined and taught under the label of 3D printing and one that has to do with the different background of the students. Students come from diverse backgrounds, meaning that they have different knowledge basis and thus different needs. Because of these challenges students not only get to acquire knowledge from different knowledge practices as it was mentioned in 6.1 but further, they learn in a rich in resources sociocultural environment. Similarly, Kostakis et al. (2015), as presented in chapter 2, also report some classroom functionality issues, related to the diversified background of the students, such as the different ICT skill level of each student and the challenging counseling provided to the students, because objects they wanted to make were complex (Kostakis et al., 2015).

As the data shows students come to be responsible for their own learning process while assembling all kinds of different assemblages in order to solve the different problems that come up, also the technical ones. This response to the different challenges is in line with the basic assumptions of the socio-material perspective, given that those consist of a social context where people use tools and artifacts to construct their knowledge. Actually, as Johri (2011) elaborates, the aim in the socio-material perspective that surpasses any problematic, is to show how the objects/materials overcome their meaning to become learning resources. By assembling resources to tackle the various challenges, the students give to the artifacts around them a knowledge construction function.

Ehud and Dror (2011) also elaborate on how the printing has production advantages and can afford the making of better products, which again (as also pointed out by Van Epps (2015)) can produce the joy of creation among students. The findings of this study support these and give specificity to what it might imply in a robotics' prototyping course. Students suggested that 3D printing is quite cheap and opts for correcting faults and making better prototypes each time, until the prototype is finalized.

As shown in chapter 5, all students agreed during the interviews that solving problems and coping with challenges was one thing they learnt during the 3D printing process and they all mentioned how they had to explore and assemble different artifacts in order to solve the different problems. These would be online video tutorials, course material from the course webpage, online forums or taking advice from their colleagues. Hovarth (2014) also describes how by surpassing problems on a 3D printing project, students not only understood better the 3D printing, but started helping others in solving their problems, by creating an environment that stimulated the team work. Arguably, in the 3D printing process students assemble artifacts during knowledge practices and when they have to solve problems within these.

In short, challenges are a very common aspect of the 3D printing process and thus very important because the process of dealing with them mediates considerable knowledge construction. Now, there be a focus further on the ways 3D printing can be useful for learning.

6.4 The Benefits of 3D printing

After all, how is 3D printing useful? Although the professor had a very clear image of how 3D printing can be useful, most students seemed a bit confused and they had to think in order to answer this question. This brings us back to the implicit mediation as described in the end of 6.1: Students would not be conscious originally of how 3D printing can be useful but after some minutes of discussion they would bring up all kinds of different functions 3D printing can have.

Some of the students mentioned how 3D printing can be useful in everyday life but in environments out of the learning one, such as work places, PhDs or hobbies. However, the researcher will emphasize on the ways that the usefulness of 3D printing is connected directly to learning. This will be also an immediate reference to the different knowledge practices and the different artifacts function of 3D printing.

Going deeper into the conversation and mostly without the interviewer intervening that much, the students usually starter thinking of other ways 3D printing was useful to their knowledge construction experience. Interesting opinions were voiced, that were moving between the secondary and the tertiary artifact function by Wartofsky (1973); it was said that 3D printing stimulates creativity and motivation, makes you think in non-usual ways, teaches you how to rethink and redesign, pay attention to details and most arguably brings your ideas out to the material world. To these opinions there is the added value of the professor's opinion which was primarily focused on creativity. For him 3D printing is useful in class because it lets students express themselves freely and allows for much creativity and improvisation. Kostakis et al. (2015) had analogous findings as he explained how 3D printing provides the learners with a different way of thinking and seeing the world, it stimulates several literacies and creativity, it inspires engagement in projects, it makes students choose what they want or need to learn and it makes it easy to materialize your ideas and share them in class (Kostakis et al., 2015).

Motivation is a very strong incentive in our findings, mentioned by all the respondents. Motivation in learning by 3D printing emerges not only in Kostakis et al. (2015) but in many research projects elaborated in chapter 2. In one of these, also Augusto et al. (2016) report how young people are no longer interested in science and technology and one basic reason, amongst others, is that there is neither technological evolution nor teaching strategies for science, especially in developing countries. For that the suggested solution is technology in the context of "Learning with Technology" through simulations and online tools. In this way, they support the use of 3D printing in class. Additionally, McGahern at al. (2015) suggests the production of replicas in Biology class with 3D printing, as the process stimulates the engagement of the students, offering a new and alternative way of approaching the biology class processes and a deeper knowledge on the objects they are willing to make.

Although this subject was not elaborated as a separate one in chapter 5, one can see how students perceive the usefulness of 3D printing through the whole chapter. To sum up, 3D printing is perceived as a useful process in many diverse ways both for the students and the professor. It is significant to take under consideration how they all elaborated on the different aspects of knowledge mediation and construction.

With this chapter, it has been explained how the findings of the study can be interpreted through the lenses of the socio-material perspective and with a focus on knowledge construction in order to give answers to the two research questions.

7 Conclusion and suggestions for further research

Going back to the very beginning, to the research questions, it should be clear how the main conclusions answer back to those. More specifically, 3D printing as a tool and a process, provides students with opportunities for exploration and knowledge construction throughout the different knowledge practices that it encompasses as well as through challenges, technological affordances and materiality. Furthermore, both the students and the professor perceive 3D printing as useful for learning purposes, as they agree that 3D printing stimulates creativity, new ways of thinking and motivation, while they also highlight how the different challenges led them through correcting mistakes and becoming better on their subject.

The analysis of this study has contributed in a way to the findings of the previous studies. What this analysis offered in addition to the ones presented in the literature review, in chapter 2, is that it is the only one that focuses in all different knowledge practices, perceiving 3D printing process as a whole and not only as a printing tool. In addition, it empowers results that are opting for 3D printing in learning environments with the perception of the students themselves and not only of the professor or an external observer. Furthermore, this is a research that took place in higher education context which has hardly happened before, when it comes to 3D printing. Also, this study includes challenges as an intrinsic part of learning and only as an additive outcome of the research. Finally, I have not come across other studies that use the socio-material perspective and not only constructivism which has been usually used for similar studies. This gives to the data a more holistic interpretation on how knowledge is constructed.

The data presented in this master thesis allows for data analysis and conclusion in the context of this higher education course, on knowledge construction, knowledge exploration and students perceptions on how 3D printing can result useful in a learning process. As such the results cannot be generalized. The master thesis context did not allow for exploration and research on more courses or projects given the size of it as well as the time span. For the same reason, there is no opportunity in the present thesis to unfold and analyze all the design processes in detail as they were observed during the participant observations and commented during the interviews. However, a valuable effort has been made to present the most important findings and provide the reader with a descent image of the processes and the methodological limitations could hopefully inspire further research on this topic.

Up to this point, I presented a summary of the main contributions of the study in the research field that concerns learning as well as the main limitations, due to the context of it. In continuation, I shall give suggestions for further research as they result from the limitations and the theoretical perspective.

7.1 Suggestions and advices for further research

The present study can be used as a stepping stone for similar studies in the future as it provides all the relevant information on theory and the interview and observation guides. However, the subject needs further exploration in more and diverse educational fields, such as history, architecture or mathematics in order to have well-founded results on the relation between 3D printing and learning. It could also reach further to different higher education groups, as for example, bachelor students, master students or PhD students and how each group can use it for learning practices. An interesting turn would also be to research if the 3D printing process facilitates learning by people with special needs such as learning difficulties or moving difficulties that do not allow for crafting activities but for computer use.

At this point it is important to elaborate on how a socio-material approach can be valuable for this kind of research project. Socio-materiality is one of the latest movements in learning theories and steps on constructivism but with an added value. What the socio-material perspective provides, as its name reveals, is a theoretical context that besides of explaining learning as a knowledge construction, also interprets how this learning happens: The shift between the material and the social world is something that was introduced quite recently in the world of constructivism and this study has shown in detail how it can be a robust base for researching learning in technology. Hence, this study is an invitation to the research world to build on the socio-material perspective as it can be a highly productive theory, with many and diverse concepts, when it comes to research how technologies are related to learning. It is arguable how technologies, existing nowadays in education in all its different aspects (from communication to learning games) are by nature combing the social and the material; it is enough for one to think how each technological apparatus consists of two parts: the software and the hardware.

7.2 Final reflections

After having elaborated suggestions for future research projects that concern not only the fields of 3D printing and learning, but also the use of relevant theoretical context, there is one thing to be added: 3D printing might not be the device that will exist in every house in the next couple of years, but as this study shows, it is an apparatus with many possibilities that can facilitate knowledge construction. It is also important that the prerequisites to use a 3D printer are relatively few as it gets simplified day by day. As the shifts in technologies and innovation call for more technology-educated students, 3D printing can be proved valuable and provide them with different technological skills. It is believed that a good start would be to introduce 3D printing in more classrooms and allow students to explore them; in other words, make 3D printing more accessible to all students.

Literature list

Ackermann, E., (2001). Piaget's constructivism, Papert's constructionism: what's the difference? Available at: http://learning.media.mit.edu/content/publications/EA.Piaget%20_%20Papert.pdf (04.10.2017).

Augusto I., Monteiro D., Girard-Dias W., dos Santos TO., Rosa Belmonte SL., Pinto de Oliveira J., et al. (2016) Virtual Reconstruction and Three Dimensional Printing of Blood Cells as a Tool in Cell Biology Education. *PLoS ONE* 11(8): e0161184. doi:10.1371/journal.pone.0161184

Bruner, J. (1977). *The process of education*. Cambridge, Mass: Harvard University Press.

Bryman, A. (2012): *Social Research methods* 5th edition, Oxford: Oxford University Press.

Chen, M., et al. (2014). Effects of a 3D printing course on mental rotation ability among 10-year-old primary students. *International Journal of Psychophysiology* 94(2): 240.

Cole, M. (1996). *Cultural Psychology: A Once and Future Discipline*. Cambridge, MA: The Belknap Press.

Cole, M. and J. Derry (2005). *We Have Met Technology and It Is Us.* Intelligence and Technology: The Impact of Tools on the Nature and Development of Human Abilities. R. J. Sternberg and D. Preiss, Lawrence Erlbaum Associates.: 209-227.

Daniels, H. (2015). Mediation: An expansion of the socio-cultural gaze. *History of the Human Sciences,* 28(2): 34.

Dean, N., et al. (2016). Applying Hand-Held 3D Printing Technology to the Teaching of VSEPR Theory. *J. Chem. Educ*. 93(9): 1660-1662.

Ehud, K. and A. Dror (2011). Enhancing aerospace engineering students' learning with 3D printing wind-tunnel models. *Rapid Prototyping Journal* 17(5): 393-402.

Fenwick, T. and R. Edwards (2011). Considering materiality in educational policy: Messy objects and multiple reals. *Educational Theory* 61(6): 709-726.

Goodyear, P. and Markauskaite, L. (2017): *Epistemic Fluency and Professional Education*. Springer Netherlands.

Gieryn, Thomas F. 2002. What buildings do. *Theory and Society* 31: 35- 74.

Guba, E. G., and Lincoln, Y. S. (1994). Competing Paradigms in Qualitative Research, in N. K. Denzin and Y. S. Lincoln, *Hanbook of Qualitative Research*. Thousand Oaks, CA: Sage.

Hope, Kristin Lofthus, H., & Norges Teknisk-Naturvitenskapelige Universitet, Det Humanistiske Fakultet. (2006). *New Knowledge Objects? Exploring Cultures of Representation in Knowledge-Intensive Work.*

Horvath, J. (2014). *Mastering 3D Printing.* Berkeley, CA, Apress: Berkeley, CA.

Horvath, J., et al. (2015). *The New Shop Class : Getting Started with 3D Printing, Arduino, and Wearable Tech*. Berkeley, CA, Apress.

Johri, A., (2011). Socio-material bricolage: The creation of location-spanning work practices by global software developers. *Information and Software Technology*, 53, 955-968.

Jonassen, D. and Land, M. S. (2012). *Theoretical Foundations of Learning* Environments, Preface, pp. vii-x. 2nd edition, NY: Routledge/Taylor and Francis Group.

Kanev, K., et al. (2012). Employment of 3D printing for enhanced kanji learning. Proceedings of the 2012 Joint International Conference on Human-Centered Computer Environments. Aizu-Wakamatsu, Japan, ACM: 165-170.

Kostakis, V., Niaros, V., Giotitsas, C. (2015). Open source 3D printing as a means of learning: An educational experiment in two high schools in Greece. *Telematics and Informatics*, 32, 118-128.

Maier, A. M., et al. (2014). Perceiving Design as Modelling: A Cybernetic Systems Perspective. *An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations.* A. Chakrabarti and L. T. M. Blessing. London, Springer London: 133-149.

Mc Gahern, P., Bosch, F., Poli, D. (2015). Enhancing Learning Using 3D Printing: An Alternative to Traditional Student Project Methods. *The American Biology Teacher*, 77(5):376-377.

Norman, D. A. (1991). *Cognitive artifacts. Designing interaction*. M. C. John, Cambridge University Press: 17-38.

Norman, D.A(1999). Affordances, Conventions and Design. *In Interactions*, 6 (3), 38-41.

Orlikowski, W.J., and S.V. Scott. 2008. Socio-materiality: Challenging the separation of technology, work and organization. *Annals of the Academy of Management 2*, no. 1: 433–74.

Orr, J., (1996). *Talking About Machines: An Ethnography of a Modern Job*, Cornell University Press, Ithaca, NY.

Papert, S., (1993). *The children's machine: rethinking school in the age of the computer.* Basic Books, New York

Paavola, Sami, Lipponen, Lasse, & Hakkarainen, Kai. (2004). Models of Innovative Knowledge Communities and Three Metaphors of Learning. *Review of Educational Research, 74*(4), 557-576.

Piaget, J. (1929/1975). *The Child's Conception of the World*. Boston: Lanham, MD (Original Translation from french 1929).

Rodenbough, P. P., et al. (2015). 3D-Printing Crystallographic Unit Cells for Learning Materials Science and Engineering. *Journal of Chemical Education* 92*(*11): 1960-1962.

Säljö, R. (1998). Thinking with and through artifacts: The role of psychological tools and physical artifacts in human learning and cognition. In D. Faulkner, K. Littleton & M. Woodhead (Eds.), *Learning relationships in the classroom*. London: Routledge.

Säljö, R. (2005). *Lärande och kulturella redskap. Om lärprocesser och det kollektiva minnet. [Learning and cultural tools. On processes of learning and collective remembering]*. Stockholm: Nordstedts Akademiska.

Säljö, R., (2010). Digital tools and challenges to institutional traditions of learning: technologies, social memory and the performative nature of learning. *Journal of Computer assisted Learning*, 26, 53-64.

Säljö, R. (2010). Learning in a Sociocultural Perspective A2 - Peterson, Penelope. *International Encyclopedia of Education (Third Edition).* E. Baker and B. McGaw. Oxford, Elsevier: 498-502.

Silverman, D., (2006). *Interpreting Qualitative Data Third Edition*. Sage Publications. Los Angeles: California.

Smiar, K. and J. D. Mendez (2016). Creating and Using Interactive, 3D-Printed Models to Improve Student Comprehension of the Bohr Model of the Atom, Bond Polarity, and Hybridization. *J. Chem. Educ*. 93(9): 1591-1594.

Tight, M., (2012). *Researching Higher Education*. SRHE/ Open University Press pp. 51-64.

Vygotsky, L. (1978). *Mind in society. The development of higher psychological processes*. Cambridge MA: Harvard University Press.

Vaccarezza, M. and Papa, V., (2014). 3D printing: a valuable resource in human anatomy education. *Anatomical Science International* 90(1): 64-65.

Van Epps, A., Huston, D., Sherrill, J., Alvar, A., Bowen, A. (2015). How 3D Printers Support Teaching in Engineering, Technology and Beyond. *Bulletin of the Association for Information Science and Technology*, 42, 1.

Wartofsky, M. (1973) *Models*. Dordecht: D. Reidel.

Wertsch, J., (1991). *Vocies of the Mind. A Sociocultural Approach to Mediated Action*, Harvard University Press, Cambridge, MA.

Wertsch, J.V. (2007). Mediation. In M. Daniels, M. Cole, & J.V. Wertsch (Eds.), *The Cambridge companion to Vygotsky* (pp. 178–192). Cambridge: Cambridge University Press.

Woolgar, Steve (1991) Configuring The User: the case of usability trials in John Law (ed.), *A Sociology of Monsters: Essays on Power, Technology and Domination,* London and New York: Routledge.

Yin, R. K. (2009). *Case study research : design and methods*. Thousand Oaks, Calif, Sage.

Websites

ASTM (American Society for Testing and Materials), 2010. Standard terminology for additive manufacturing technologies. ASTM F2792-10. Available at: http://www.astm.org/Standards/F2792.htm, 04.10.2017

http://global.britannica.com/technology/3D-printing, 04.10.2017

http://www.teachthought.com, 04.10.2017

http://dictionary.cambridge.org/dictionary/english/represent, 04.10.2017

Appendix

Appendix 1. Observation scheme

Date/Number of Session:
Reference Number of Participants:
Number of Students:
Presence of Professor: ☐

Time-Duration	Activity (Aims, Objectives, Main content)	Knowledge Content	Activity (Printing, Reading material, Using software)	Knowledge Resources used or Referred to (Reading Resources, Software, Hardware, Documentation, Sources of Information)	Comments	Notes

Appendix 2. Interview guide for students

On the background:

-What is your educational background before this course?

-What is the reason you are following this course? Is it mandatory or optional in your program?

-Do you have any previous experience on 3D printing?

On Designing:

-Could you describe your designing process?

-What did you attempt while designing? Which were your original intentions? Did that work out for you?

-How did you organize the designing process? Did you decompose it to smaller parts and if so did that had to do with the 3D printing?

- How would you say designing helped you learn?

-What kind of challenges did you have while designing? How did you faced them?

On the learning opportunities:

-How would you say that 3D printing helped you learn?

- What would you say you learnt through this process?

- Is there something that you have the opportunity to explore further due to the use of the 3D printer? (Maybe on materials, modelling skills).

-Would you say that working with a 3D printed was related to the inspiration you had for designing your robot?

-Would you say that having a project on 3D printing made you think ahead on your designing process or the materials you were going to use?

On Challenges

- How did you experience challenges while working on your assignment using 3D printing? What kind of challenges were there? How did you cope with them? (Designing problems –many chose to start all over again-, printing problems- searching for solutions online by themselves)

-Would you say that these challenges helped you go further?

-What tools would you say that you used during your assignment?

- What kind of knowledge was available for you, while using the 3D printer? (lectures, online material)

On perception of usefulness of the 3D printers adding on the observed activities:

-How did you experience the use of 3D printing?

- In what ways do you think the use of a 3D printer was useful?

- What do you think that would be different if you were to perform the same assignment without the use of 3D printing?

-To what point do you think that the experience of using 3D printing played a role for your engagement to the assignment?

Closing:

-If you were to take the course again now, what would you do differently?

-What advices would you give to the professor in order to further develop the learning potential of the course?

*Would you like to add something on our discussion?

*Thank you very much for your time and for allowing me to interview you.

Appendix 3. Interview guide for the professor

Background

-Why was the course put together? Is it a part of a wider program structure?

-How long have you been teaching the course?

-Was the course already running when you started? To what extent has the course been (re)designed and why?

Activities and Organization

-Can you tell me a bit more about the focus of the course?

- I could see online that the main learning outcomes are the understanding and use of CAD and CNC, the understanding and control of the basic robot actuators, of programing microcontrollers and build and operate a CNC milling machine.

Could you describe them further or comment on them?

-Would you say there are any other aims or objectives of the course, can you please describe them?

-Can you tell me a bit more about the tasks that students have to do in the course?

-What kind of learning activities take place with the 3D printer? Have there been any changes and why?

-What would you characterize as a successful student in these tasks?

-Do the students have any support available when working on these tasks? (teacher present, supervision).

-What happens with the printed products? Will they be assessed by you? If so, how?

-Why do they work individually or in groups of maximum 3 people?

-What other learning resources are being used in the class and how are they related to the 3D printing (CAD, CNC, electronics, actuators, books)?

-Why did you choose for your students to work with 3D printers for this course?

-In what ways to you think the use of 3D printing influences or supports the students' learning?

Knowledge

-What kind of knowledge are students supposed to receive from the course?

-What kind of skills are students supposed to gain in the course?

- On the website there are some prerequisites for the course:

Is there anything more you would like to add on these? Are these prerequisites important to understand new knowledge (as a basis) or the students will use these and elaborate them further?

-Have you noticed anything you would consider noteworthy on what students learn during the course? Or on how they learn it?

(In previous conversation: new ideas/ they students learn a lot on materials and mechanical aspects)

General Questions

- What challenges have you experienced, while using 3D printers in course activities?

-What is your general experience of the course?

*Is there anything that you would like to add before we end this conversation?

*Thank you for your time and for allowing me to interview you.

Appendix 4. Consent letter and invitation to the students

Invitation to participate in research project on the influence of 3D printing in learning in higher education

To ……………………,

Many thanks for your willingness to participate in an interview and in the participant observations conducted as part of my master thesis work at the Faculty of Education, University of Oslo. I am a student at the European Master program in Higher Education, and my thesis focuses on how the process of 3D printing can influence learning in higher education. The existing research literature shows some encouraging results on the ways that 3D affects the way of thinking, strengthens memorizing, aids modelling skills and provides deeper knowledge on the materials one is working with. My interest is to explore what opportunities for exploration and knowledge construction are accessible while working with 3D printing and how its usefulness is perceived by teacher and students. I will use the master program in Robotic Prototypes as a case study for my analysis. This program is selected because of its capacity to provide rich information about the research questions and due to the fact that it is currently the only course in the University where 3D printing is used regularly.

Methodologically, the thesis will be based on interviews and participant observations during the course. Some of the observation sessions will be videotaped and photographs will be taken if you voluntarily agree on the process. The data will be used for the purpose of research for my master thesis only. The information will be handled in accordance with the Personal Data Act. Your personal name or the University name will not be mentioned in my thesis, but details on the study program will be mentioned where it is considered indispensable. As a point of reference regarding the interview, you will be referred to as the "respondent" or "interviewee", not by your personal name. For the sake of securing correct information I would like to record the interview.

What will happen to the information about you?
All personal data will be treated confidentially. Data will be accessible only by me (Drakoulaki Aikaterini) and my supervisor, as long as the study lasts, and everything will be secured under password.

The project is scheduled for completion by the latest, the end of December 2017. After the completion of the Master thesis all data will be deleted.

Voluntary participation
It is voluntary to participate in the project, and you can at any time choose to withdraw your consent without stating any reason. If you decide to withdraw, all your personal data will be made anonymous.
If you would like to participate or if you have any questions concerning the project, please contact me:

Drakoulaki Aikaterini
Phone number: (+47) 40475321
e-mail: aikaterinidrakoulaki@gmail.com

Or my supervisor:

Monika B. Nerland
Phone number: 22 85 81 72
e-mail: monika.nerland@ped.uio.no

The study has been notified to the Data Protection Official for Research, NSD - Norwegian Centre for Research Data.

Consent for participation in the study

I have received information about the project and I am willing to participate

----
(Signed by participant, date)

In case where it is beneficial for the study to video record the session or take photographs of the activity taking place:

○ I have no problems with this

○ I will consider the situation before I give my consent to this

Appendix 5. Consent letter and invitation to the professor

Invitation to participate in research project on the influence of 3D printing in learning in higher education

To………………………..,

Many thanks for your willingness to participate in an interview and in the participant observations conducted as part of my master thesis work at the Faculty of Education, University of Oslo. I am a student at the European Master program in Higher Education, and my thesis focuses on how the process of 3D printing can influence learning in higher education. The existing research literature shows some encouraging results on the ways that 3D affects the way of thinking, strengthens memorizing, aids modelling skills and provides deeper knowledge on the materials one is working with. My interest is to explore what opportunities for exploration and knowledge construction are accessible while working with 3D printing and how its usefulness is perceived by teacher and students. I will use the master program in Robotic Prototypes as a case study for my analysis. This program is selected because of its capacity to provide rich information about the research questions and due to the fact that it is currently the only course in the University where 3D printing is used regularly.

Methodologically, the thesis will be based on interviews and participant observations during the course. However, to secure that I have access to relevant information and to get a better insight into the pedagogical intentions of the activities, I would like to include an interview with you as director of the program.
The data will be used for the purpose of research for my master thesis only. The information will be handled in accordance with the Personal Data Act. Your personal name or the University name will not be mentioned in my thesis, but details on the study program will be mentioned where it is considered indispensable. As a point of reference regarding the interview, you will be referred to as the “respondent” or “interviewee”, not by your personal name. For the sake of securing correct information I would like to record the interview.

What will happen to the information about you?
All personal data will be treated confidentially. Data will be accessible only by me (Drakoulaki Aikaterini) and my supervisor, as long as the study lasts, and everything will be secured under password.

The project is scheduled for completion by the latest, the end of December 2017. After the completion of the Master thesis all data will be deleted.

Voluntary participation
It is voluntary to participate in the project, and you can at any time choose to withdraw your consent without stating any reason. If you decide to withdraw, all your personal data will be made anonymous.
If you would like to participate or if you have any questions concerning the project, please contact me:

Drakoulaki Aikaterini
Phone number: (+47) 40475321
e-mail: aikaterinidrakoulaki@gmail.com

Or my supervisor:

Monika B. Nerland
Phone number: 22 85 81 72
e-mail: monika.nerland@ped.uio.no

The study has been notified to the Data Protection Official for Research, NSD - Norwegian Centre for Research Data.

Consent for participation in the study

I have received information about the project and I am willing to participate

----
(Signed by participant, date)

Appendix 6. Approval by the Norwegian Data Protection Official for Research

Monika Bærøe Nerland
Institutt for pedagogikk Universitetet i Oslo
Postboks 1092 Blindern
0317 OSLO

Vår dato: 13.12.2016 Vår ref: 51279 / 3 / AMS Deres dato: Deres ref:

TILBAKEMELDING PÅ MELDING OM BEHANDLING AV PERSONOPPLYSNINGER

Vi viser til melding om behandling av personopplysninger, mottatt 25.11.2016. Meldingen gjelder prosjektet:

51279	*Facilitating the process of learning using 3D printing in a Robotics Masters Course*
Behandlingsansvarlig	*Universitetet i Oslo, ved institusjonens øverste leder*
Daglig ansvarlig	*Monika Bærøe Nerland*
Student	*Aikaterini Drakoulaki*

Personvernombudet har vurdert prosjektet og finner at behandlingen av personopplysninger er meldepliktig i henhold til personopplysningsloven § 31. Behandlingen tilfredsstiller kravene i personopplysningsloven.

Personvernombudets vurdering forutsetter at prosjektet gjennomføres i tråd med opplysningene gitt i meldeskjemaet, korrespondanse med ombudet, ombudets kommentarer samt personopplysningsloven og helseregisterloven med forskrifter. Behandlingen av personopplysninger kan settes i gang.

Det gjøres oppmerksom på at det skal gis ny melding dersom behandlingen endres i forhold til de opplysninger som ligger til grunn for personvernombudets vurdering. Endringsmeldinger gis via et eget skjema, http://www.nsd.uib.no/personvern/meldeplikt/skjema.html. Det skal også gis melding etter tre år dersom prosjektet fortsatt pågår. Meldinger skal skje skriftlig til ombudet.

Personvernombudet har lagt ut opplysninger om prosjektet i en offentlig database, http://pvo.nsd.no/prosjekt.

Personvernombudet vil ved prosjektets avslutning, 31.12.2017, rette en henvendelse angående status for behandlingen av personopplysninger.

Vennlig hilsen
Kjersti Haugstvedt

Anne-Mette Somby

Kontaktperson: Anne-Mette Somby tlf: 55 58 24 10

Dokumentet er elektronisk produsert og godkjent ved NSDs rutiner for elektronisk godkjenning.

Vedlegg: Prosjektvurdering

Kopi: Aikaterini Drakoulaki aikaterinidrakoulaki@gmail.com

Personvernombudet for forskning

Prosjektvurdering - Kommentar

Prosjektnr: 51279

The sample will receive written and oral information about the project, and give their consent to participate. The letter of information is well formulated.

The Data Protection Official presupposes that the researcher follows the routines of Universitetet i Oslo regarding data security. If personal data is to be stored on a private computer, the information should be encrypted.

Estimated end date of the project is 31.12.2017. According to the notification form all collected data will be made anonymous by this date.

Making the data anonymous entails processing it in such a way that no individuals can be recognised. This is done by:

- deleting all direct personal data (such as names/lists of reference numbers)
- deleting/rewriting indirectly identifiable data (i.e. an identifying combination of background variables, such as residence/work place, age and gender)
- deleting digital audio and video files

Appendix 7. Technical Terms

Blender: design software

CAD/ CAD program: Computer-Aided Design. Refers to designing software

Cura: software that virtually places the object to the printer and sens it to print

Extrude: a function used when designing, where one can take a 2D sketch and virtually stretch it out to a 3D one

Filleting: a function used on designing to make the edges softer on a design which cuts out material so it helps in faster printing and the use of less material

Mirror: a function used on designing and concerns the duplication of left side to the right one

Send to printer: through software one gives to the printer the command to print an object

Support/ support material: some kind of material needs to be put virtually before the object is sent to the printer and then also printed. This material is less robust than the actual object and it is used because if there are gaps between the printed object and the base of the printer without support, then the object is somehow melting down and the result is not the previewed one. The support material is taken off after printing. The support material can be the same as the printing material and it can be water-solvable or sand-papered.

Solidworks: design software

ScreentoGif: gif making software for making gifs of the printing layers for the purposes of the course

Ultimaker/ Objet: Different brands of printers that print in different ways and by using different materials.