Ari Pikkarainen

# DEVELOPMENT OF LEARNING METHODOLOGY OF ADDITIVE MANUFACTURING FOR MECHANICAL ENGINEERING STUDENTS IN HIGHER EDUCATION

ACTA UNIVERSITATIS LAPPEENRANTAENSIS 969

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# DEVELOPMENT OF LEARNING METHODOLOGY OF ADDITIVE MANUFACTURING FOR MECHANICAL ENGINEERING STUDENTS IN HIGHER EDUCATION

Dissertation for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium 1316 at Lappeenranta-Lahti University of Technology LUT, Lappeenranta, Finland on the 7th of July, 2021, at noon.

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# Abstract

**Ari Pikkarainen**
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The main aim of this thesis was to research the learning of additive manufacturing (AM) and the impact of using multiple AM technologies as a form of learning. The goal was to develop a new methodology for learning additive manufacturing in universities and universities of applied sciences and improve the AM knowledge transfer from higher education institutions to companies and industrial actors. The research work was connected to the development of AM education and to the design of the Lapland UAS mechanical engineering degree program´s new AM laboratory.

Additive manufacturing is a method where an object is manufactured layer by layer from 3D CAD data. Seven different AM technologies exist, from which three of the most used ones are polymer-based printing technologies: material extrusion, vat photopolymerization and powder bed fusion of polymers. AM is on the verge of becoming recognized as one of the basic manufacturing methods and in order to make this happen, a methodology for AM education must be developed. The speed of technological development in AM is faster than AM education development; educational units such as universities and universities of applied sciences need efficient and organized methods in order to produce AM professionals according to the requirements of work-life. This happens by organizing practical AM learning environments and implementing AM into the curricula of engineering degree programs. This positively impacts society through the employment of educated AM professionals. Through this, knowledge related to AM increases in companies as they are more aware of the possibilities to use AM in their operations. The identification of learning based on AM and its pedagogical development are important, since AM learning is inversely related to AM requirements, which are connected to the experience level of students. The basic nature of engineering must be connected to AM principles by identifying the need for pedagogical development.

Traditional pedagogics need an updated perspective on the implementation of AM in engineering education. AM is a relatively new technology and traditional pedagogics are not fully suitable for its implementation. The model of technical pedagogics provides a tool for AM´s more efficient implementation into curriculum. The practical arrangement of AM education needs an occupationally safe and practical learning environment and a function model in order to implement the AM studies according to a curriculum. The fundamentals of learning are based on learning outcomes and by mapping the needs of work-life related to AM education; thus, the AM knowledge transfer from university to work-life should be efficient. To accomplish this, engineering students´ learning of AM must be investigated. The use of multiple technologies in AM education improves students´ learning and therefore increases their knowledge and skill level.

Keywords: additive manufacturing, 3D printing, learning environment, pedagogy, curriculum, learning outcome, technical pedagogy, knowledge transfer, multiple technologies.

# Acknowledgements

I have worked on this thesis during the years 2018 – 2021 while working as a senior lecturer at Lapland University of Applied Sciences in the mechanical engineering degree program. This thesis forms the highlight of my academic career as it gives me the opportunity to achieve the highest academic degree possible. The dream of becoming a D.Sc. started to brew in my mind some years ago after my M.Sc. studies. My motivation towards academic research grew as I was able to combine my profession as a teacher with the area of additive manufacturing.

I want to thank Professor Heidi Piili for being my mentor and main motivator starting from my M.Sc. studies. Without your burning enthusiasm and the ability to motivate your students, I would not to be where I am now in my academic career. You showed me, what academic research actually is and also the funny side of it; research does not always have to be so serious. I would also like to express my gratitude to Manufacturing 4.0 (MFG4.0) project which provided me support and knowledge base for this thesis.

I want to thank professor Antti Salminen for giving me the opportunity to start my D.Sc. studies and being an active supporter in my academic path. I have learnt a lot about academic writing from you as you were a co-writer on my research papers.

I want to thank my reviewers industry professor Iñigo Flores Ituarte, D.Sc. (Tech.) (University of Tampere) and program director Maximilian Lackner, Ph.D. (University of Applied Sciences Technikum Wien) for reviewing this manuscript and offering comments and suggestions for improving this thesis. I am deeply thankful to Maximilian Lackner for being also the opponent in my dissertation.

I am grateful to Lapland UAS for giving me the opportunity to connect my work to my D.Sc. studies and supporting me in my studies in so many ways that I cannot even start to describe. My work means so much to me and the possibility to connect my studies to my work means the world to me.

These past three years have been the most difficult time of my life due to many reasons and this thesis has been my lifebelt in so many ways. This process showed me that despite the difficulties you have in your life, having a goal will keep you motivated and focused. The loved ones in my life (you know who you are) have supported me and encouraged me to go forward, no matter what life throws into my path. For that, I am eternally grateful to you. Forward, that is the only direction to go.

Ari Pikkarainen
June 2021
Kemi, Finland

# Contents

# List of publications

This thesis is based on the following papers. Publishing rights have been granted for including these papers in this dissertation.

I. Pikkarainen, A., Piili, H., and Salminen, A. (2017). Creating learning environment connecting engineering design and 3D printing. *Physics Procedia,* 89, pp. 122–130.

II. Pikkarainen, A., and Piili, H. (2020). Implementing 3D printing education through technical pedagogy and curriculum development**.** *International Journal of Engineering pedagogics,* 10(6), pp. 95-119.

III. Pikkarainen, A., Piili, H., and Salminen, A. (2020). The design process of an occupationally safe and functional 3D printing learning environment for engineering education. *European Journal of Education Studies*, 7(12), pp. 80 –105.

IV. Pikkarainen, A., Piili, H., and Salminen, A. (2021). Introducing novel learning outcomes and process selection model for additive manufacturing education in engineering**.** *European Journal of Education Studies*, 8(1), pp. 64 – 88.

V. Pikkarainen, A., Piili, H., and Salminen, A. (2021). Perspectives of mechanical engineering students to learning of additive manufacturing – learning through multiple technologies. *International Journal of Innovation and Research in Educational Sciences*, 8(1), pp. 35-54.

# Author's contribution

Ari Pikkarainen is the main author and researcher in publications I – V.

Publication I. The author conducted the research and drafted the results based on his work as a senior lecturer in Lapland UAS. The research was conducted under the supervision of professors Antti Salminen and Heidi Piili.

Publication II. The author conducted the research in collaboration with professor Heidi Piili, performed the literature review and produced the results presented in the article together with the conclusions.

Publication III. The author conducted the research under the supervision of professors Heidi Piili and Antti Salminen, performed the literature review, implemented the design work based on the Lapland UAS 3D printing laboratory renewal project and designed the models and results presented in the article together with the conclusions.

Publication IV. The author conducted the research under the supervision of professors Heidi Piili and Antti Salminen, performed the literature review, conducted the work-life questionnaire, analysed the results and created the learning outcomes and conclusions.

Publication V. The author conducted the research under the supervision of professors Heidi Piili and Antti Salminen, performed the literature review and conducted the 3D printing course with Lapland UAS mechanical engineering degree students. The author conducted the student questionnaire, analysed the results and made the final conclusions.

# Nomenclature

| | |
|---|---|
| AM | Additive manufacturing |
| CDIO | Conceive – Design – Implement – Operate |
| DfAM | Design for additive manufacturing |
| EQF | European Qualifications Framework |
| HEI | Higher education institution |
| I-U | Industry to university |
| LrBL | Literature review-based learning |
| NQF | National Qualifications Framework |
| PBL | Problem-based learning |
| PD | Product design |
| PjBL | Project-based learning |
| R&D | Research and development |
| STEM | Science, technology, engineering and mathematics education |
| U-I | University to industry |

# 1 Introduction

## 1.1 Background and motivation

Additive manufacturing (AM), also known as 3D printing, is a relatively new industrial manufacturing method in addition to traditional methods such as welding, turning and milling. The speed of technological development has revealed the need for renewal of the educational arrangement of AM; universities, universities of applied sciences and other educational units need proper pedagogical methods and guidelines for implementing AM education. When looking at the situation in Finland, many universities and educational units practice AM in their courses but the arrangement can still be seen scattered and unorganized since there are no existing traditions or standardised ways to arrange AM education in the current literature (Ketola, 2020; Lindqvist et al., 2016). As stated by Lindqvist et al. (2018), the level of AM knowledge especially in industrial applications in Finland, can be seen as rather low. This emphasizes the need for the training of AM experts through proper education. The general obstacles for the introduction of AM in companies in Europe (as well as in Finland) is the lack of know-how, knowledge and a deeper understanding of the possibilities of the technology. This is one consequence of the lack of proper AM education in Europe and Finland especially in the curricula level (Duchêne et al., 2016). Many companies whose primary functions are based on traditional manufacturing methods are facing this problem since their functions, such as manufacturing chain and product development, are based on traditions that are sometimes difficult to change. In addition, these traditions can be seen as cultural barriers in the manufacturing sector that need to be overcome especially when looking at the distribution of AM in manufacturing chains (Duchêne et al., 2016). One obvious reason for this is the gap in the current research, since the literature does not provide clear and applicable methods for arranging AM education, e.g. in engineering education, nor does it discuss the fundamentals of these methods (Pikkarainen, Piili and Salminen, 2020). This sets demands for universities and universities of applied sciences to develop up-to-date AM expertise which can be transferred to companies through graduated students. These higher education institutions (HEIs) provide AM education in Finland from different perspectives and are in focus regarding the use of the results of this thesis. The main task of Finnish universities is to provide higher education based on research. Other tasks include academic research and sociological influencing together with industrial training activities (Finlex, 2009). The main task of universities of applied sciences is to provide higher education in professional expertise based on work-life requirements. This includes applied academic research with professional aspects together with development and innovation functions (Finlex, 2014). The role of HEIs is becoming more and more significant as the provider of AM expertise (Mehta and Bernadier, 2019). By developing new pedagogical methods together with guidelines for AM education, the competitiveness and viability of companies increase as they employ educated AM experts who are more aware of the possibilities of using AM in companies. In this thesis, pedagogical methods refer to the pedagogical arrangement of AM education, not only to the development of AM-based curriculum and learning outcomes but also to the description of technical pedagogy. In addition, this kind of development of AM education has a positive effect on the economy from a societal point of view (Kircheim et al., 2017; Ford and Minshall, 2019; Daniel et al., 2018; Ilg et al., 2019).

## 1.2 Scope and objectives

The main objective of this dissertation is to study different factors related to the learning of AM and to develop pedagogical and practical arrangements in order to implement AM education based on work-life needs. The aim is to understand what are the efficient ways to learn AM at B.Sc. and M.Sc. levels of engineering. In addition, the goal is to create a novel learning methodology for AM education taking the technical aspects into account.

The main objective is divided into part objectives as presented in Figure 1.

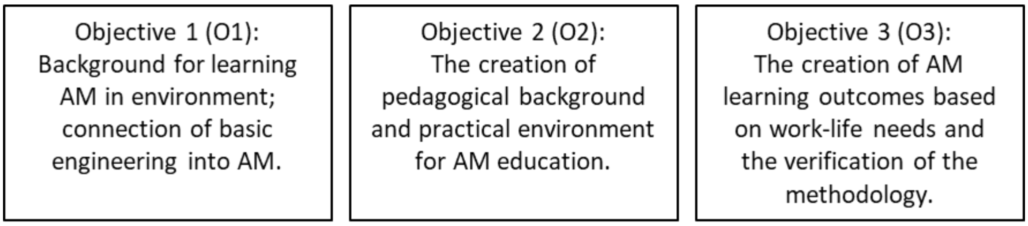


Figure 1. Objectives of the thesis.

As seen in Figure 1, the objectives have been derived from the main objective and they present three important parts of this thesis:

O1. To create an informational background for learning AM and connecting the traditional engineering education principles to it. This objective is meant to investigate the fundamentals of AM learning and engineering design education. This objective gives the background for creating an AM learning environment in conceptual sense and gives a view of the fundamentals of learning.

O2. To create the pedagogical background and practical arrangement for AM education in engineering. This objective aims to form the pedagogical and practical foundation to the learning of AM in order to create an environment where AM learning can be implemented in order to achieve the main objective of this thesis. This objective derives from the need to fill the gap in the current literature concerning the pedagogical and practical arrangement of AM.

O3. The creation of novel learning outcomes for AM learning based on work-life needs and the verification of the methodology connected to AM learning. This objective is meant to verify the quality and functionality of AM education according to work-life demands.

## 1.3 Research overview

This chapter gives a general overview and foundation to the research and presents the main research problem as a start for the research, i.e. "*the lack of pedagogical solutions for AM education*". As presented earlier, there is a need for proper pedagogical arrangement for AM education. The need for AM know-how in companies is increasing for wider application of AM in the operations of the companies. This presents a societal need for this study, as the increase of AM use presents the possibility for improving viability and competitiveness in companies. In addition, this creates the educational need as the arrangement of AM education is the key factor in spreading the AM knowledge to companies. The research questions (RQs) have been derived from the research purpose and objectives and they are:

RQ1: How can traditional engineering education be combined with AM?

RQ2: What kind of pedagogical and practical solutions does AM education require?

RQ3: How does the learning of AM work with multiple technologies?

RQ1 creates a view into combining AM into traditional engineering education and helps to understand the necessary factors behind this thesis. The factors are related to learning of traditional engineering design and AM and this research question generates the results needed to implement AM in engineering education. RQ2 creates the pedagogical and practical arrangement for AM education and presents the methodological foundation for this thesis. This fills the current gap in the literature, i.e. the lack of pedagogical solutions for AM education. In addition, this research question generates solutions for the practical arrangement of AM education. RQ3 aims to give answers to this thesis by verifying the learning methods presented in this thesis by presenting the feedback from engineering students regarding the learning and use of multiple AM technologies. The arrangement of the learning is based on the learning outcomes which have been drafted based on the needs of work-life.

This thesis consists of five publications (from here on referred as P1-P5) and the topics are as follows:

P1: The creation of the learning environment concept connecting engineering design and AM.

P2: The implementation of AM education and the creation of the concept of technical pedagogy together with AM-based curriculum development.

P3: Presentation of the design process of an occupationally safe and functional AM learning environment.

P4: The creation of novel learning outcomes for AM education based on the requirements of work-life. The creation of an AM process selection model for learning purposes.

P5: Mechanical engineering students' perspectives to learning additive manufacturing with multiple AM technologies.

Connection between objectives O1-O3 of this thesis and research questions RQ1-RQ3 and publications P1-P5 are shown in Figure 2.

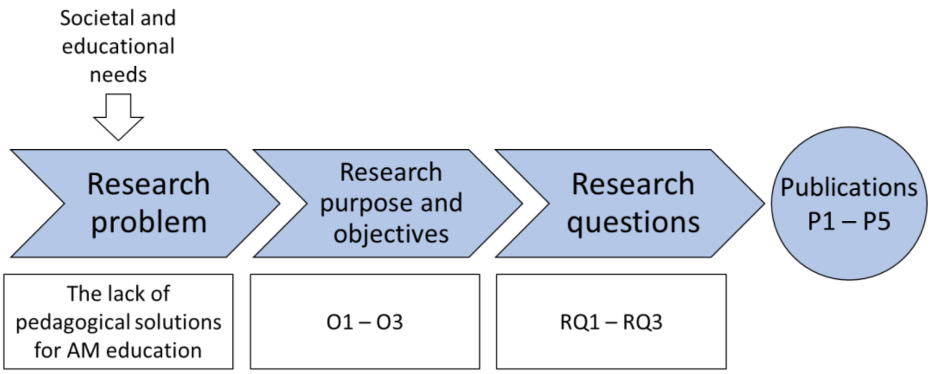


Figure 2. Research overview of this thesis.

As seen in Figure 2, the thesis starts from the societal and educational need for arranging AM education. The main research problem "*The lack of pedagogical solutions for AM education*", forms the foundation of this thesis. This generates the research purpose for this thesis and the objectives O1-O3. The research questions RQ1-RQ3 have been derived from the objectives and publications P1-P5 present the results from the conducted research in order to give answers to the research questions.

## 1.4 Thesis structure

This doctoral dissertation is based on five publications (P1-P5) and consists of three parts. Figure 3 presents the structure of the thesis including the publications, objectives and research questions to give an understanding of their places in this thesis.

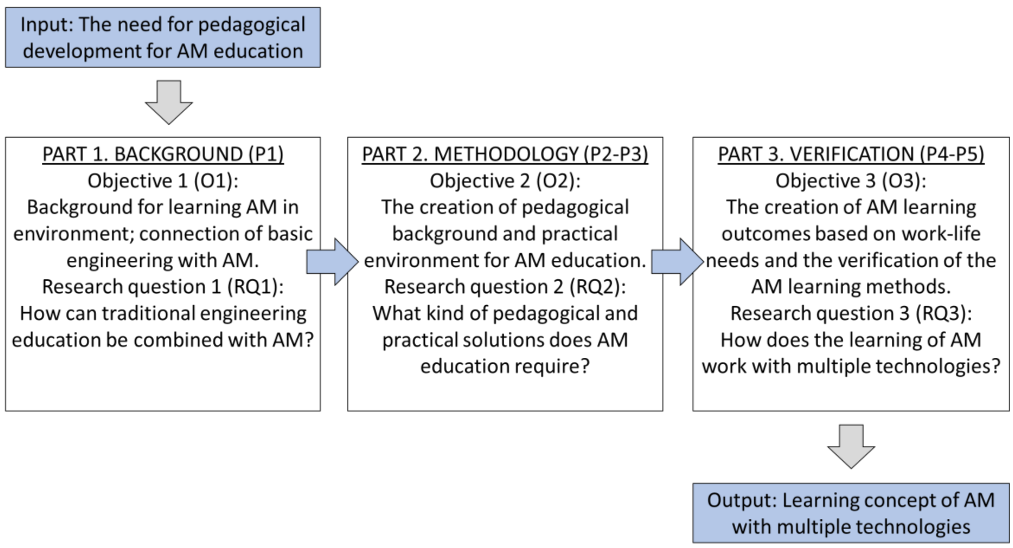


Figure 3. Structure of the thesis.

As seen in Figure 3, the input for this thesis is the need for pedagogical arrangement of AM education. The first part forms the background for connecting traditional engineering education with AM and it is based on publication P1. The second part presents the methodological section of this thesis and creates the pedagogical foundation for AM education. In addition, the second part presents the practical arrangement of AM education and it is based on publications P2 and P3. The third part verifies the pedagogical and practical design solutions with the creation of AM learning outcomes based on work-life needs and by collecting mechanical engineering students´ perspectives to learning AM with multiple polymer printing technologies. The third part is based on publications P4 and P5. The structure of the thesis, as presented in Figure 3, is based on the research overview of this thesis as presented in Figure 2.

## 1.5 Scientific contribution

This thesis is focused on the development of pedagogical methodology for AM education and the creation of the learning the concept for AM. The main scientific contributions of this dissertation are:

1) The understanding of pedagogical factors in the learning of AM, especially through curriculum development and the creation of novel learning outcomes for AM education based on work-life needs. These are discussed in P1 and P2.

2) The arrangement of AM education in engineering; the presentation of practical solutions for arranging an occupationally safe 3D printing learning environment. This is discussed in P3.

3) The selection process for the most suitable AM process based on the three most used polymer printing technologies. This concept is created from the learning point of view and it can be expanded into other AM processes. This is discussed in P4.

4) The improvement of knowledge level in companies related to the possibilities of AM through graduated students who are employed in companies. P5 discusses the evolution of AM learning with one mechanical engineering student group from Lapland UAS.

These issues are addressed and discussed in detail in the part: Publications.

# 2 Theoretical background

## 2.1 Additive manufacturing

Additive manufacturing (AM), more widely known as 3D printing, is a manufacturing technology enabling a direct manufacturing of a product from a 3D CAD model. The CAD model is sliced into thin layers each representing a manufacturable section from the part. The actual manufacturing happens layer by layer in an AM process. Due to the layer by layer approach, AM offers a large freedom for design work and it enables a more simplified manufacturing process compared to traditional subtractive processes such as turning and milling; manufacturing does not need, e.g. detailed process planning even if more complex geometries are manufactured (Gibson et al., 2021). There are different ways to categorize the AM processes but the standardized way to name the processes is based on the EN ISO / ASTM 52900:2017, (2017) standard. The processes are presented in Appendix A in detail. The seven standardized AM process categories are binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization. These represent the names of the technologies based on the baseline technology name without defining the used material. In addition, this definition type can be seen as a description of a series of phases used in the process such as the material definition, how the material is distributed or how the material is converted (e.g. in powder bed fusion the material is in powder a form and it is distributed through bed and the powder particles are fused together (Kumar, 2020).

These seven additive manufacturing technologies each have their own special characteristics and application area. *Material extrusion* presents the most used one of these and it is used in when fast prototypes from a design with low cost and high speed are needed. Used materials are generally different polymers but in addition, material extrusion allows the use of composite materials with a more advanced nature such as fibre-enforced polymers. In this thesis, the commercial term FDM (fused deposition modelling) is used when discussing the technology in the publications. *Material jetting* presents a manufacturing method enabling multi-colour and high-resolution and even multiple materials with a combination of, e.g. plastic and rubber. Typical applications for the technology are casting, parts with full colour and over-moulded plastic parts. Used materials are typically wax, different polymer-type and elastomeric materials. *Binder jetting* technology is aimed typically for visual- or, light-duty functional prototyping and when using elastomeric infiltrant, parts can even be used in functional purposes. Due to weaker strength, the visual prototype is the typical application. Used materials are typically powder made out of gypsum, sand or even metal powder. *Powder bed fusion* presents better freedom to the design with polymer materials, as there is no need for support materials during printing. With metals, different support materials are required due to the nature of the material behaviour (e.g. the dissipation of heat). Possible applications cover a wide variety of areas such as aerospace, biomedical and electronics. Materials used in powder bed fusion can be divided into polymers / composites and metals / composites. In this thesis, the commercial term SLS (selective laser sintering) is used when discussing the technology in the publications. *Directed energy deposition* covers different technologies connected with, e.g. laser engineering with near net-shape applications to melt material as it is deposited. The applications are typically for repair purposes or adding new material to existing structures. The accuracy and surface finish quality often require post-processing (usually machining). Used materials are different metallic materials in powder or wire-like form. *Vat photopolymerization* enables high accuracy and resolution for manufactured parts. This makes it ideal, e.g. for biomedical and prototyping applications where good surface finish and small details are required. Used materials are UV curable photopolymer resins and certain polymer-ceramics with hybrid properties. In this thesis, the commercial term SLA (stereolithography) is used when discussing the technology in the publications. *Sheet lamination* is probably the less known of AM technologies. With the technology, large parts can be manufactured relatively fast and the build materials present a large variety of substances such as paper and polymer sheets, metallic- or ceramic-filled tapes. In addition, costs are low compared to other AM technologies and the parts are non-toxic and stable (Diegel et al., 2020; Statista, 2019; Gibson et al., 2021; Ngo et al., 2018). AM has been regarded as a part of the 4$^{th}$ industrial revolution as it offers the possibility to create unique products with a high level of customization compared to the costs and efficiency of mass production (EEF, 2019; Krafft et al., 2020). AM is stated in many cases and research work to provide large freedom for design but despite this, AM introduces different kind of restrictions and design guidelines compared to traditional manufacturing methods. At its best, AM offers flexible, economical and fast ways to produce parts but if these design considerations and demands are not met, the reality can be totally opposite (Diegel et al. 2020; Ferchow et al., 2018; Kircheim et al., 2018).

## 2.2 Fundamentals of learning

Traditional ways to learn are changing as there is a growing demand and need for trained experts who are able to work in transdisciplinary areas of science and especially engineering. This sets demands for HEIs as their role is becoming more significant in educating future professionals who are able to contribute to the global and societal development of technology and economics (Hernandez-de-Menendez et al., 2020). The modern way to learn is based on know-how-oriented learning where traditional course-based lecturing is replaced with the pursuit of know-how and learning goals to be achieved during the learning process. This kind of learning is derived from the requirements from work-life and from the know-how needed there and is used in Finland especially in the universities of applied sciences. Group activities and social interaction are important factors in this kind of learning. Competence areas (e.g. mathematical competence or mechanical competence) and learning outcomes derived from these describe the achieved learning and know-how after the completion of a degree (Kangastie and Mastosaari, 2016b). The principle of know-how-oriented learning can be seen in Figure 4.

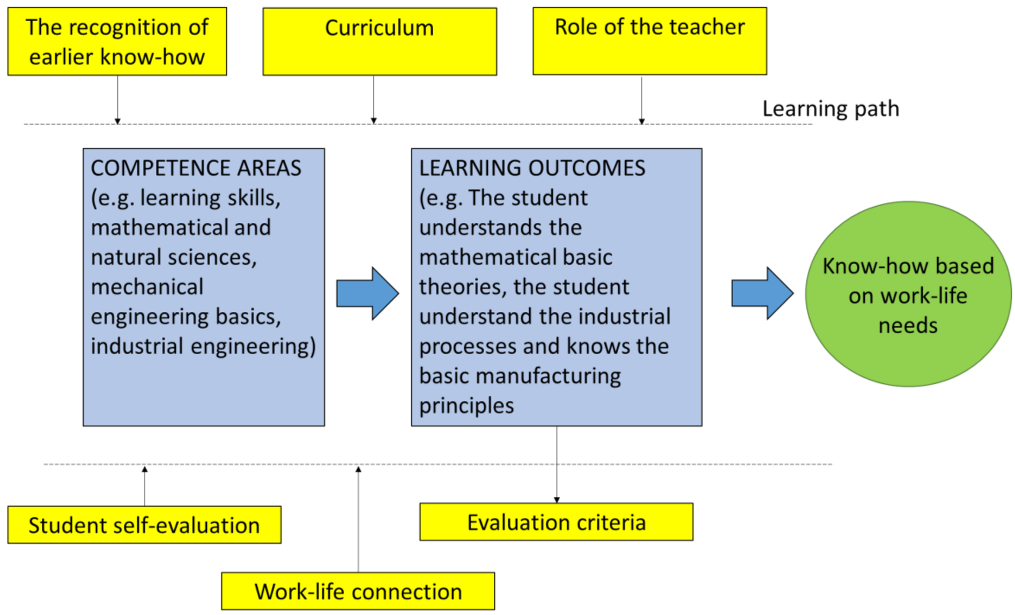


Figure 4. Principle of know-how-oriented learning (Applied from Kangastie and Mastosaari, 2016b; Alaniska et al., 2019).

As seen in Figure 4, the learning path consists of two main parts, competence areas and learning outcomes derived from the competence areas. The competence areas are a combination of general competences (e.g. learning skills and ethical skills) and professional competences (e.g. mathematical and natural sciences, mechanical engineering basics). By analysing the competence areas, the required learning outcomes can be derived from those. Learning outcomes ensure that the skills described in the competence areas are achieved (Kangastie and Mastosaari, 2016b). In addition, the path to learning can be seen in a wider perspective as presented by Alaniska et al. (2019); competences and learning outcomes are not the only factors related to know-how-oriented learning. The student can possess earlier know-how (e.g. he/she has previous studies or training from a certain area) which can be recognized as a part of a degree. This is one element in enabling the individual learning path for a student. The student´s self-evaluation in different phases of the path is important, working as a guiding element for the learning. The work-life connection, especially in drafting the competence areas is important, this ensures that the student achieves know-how based on the needs of work-life. In order to ensure the learning outcomes, a proper evaluation criterion must exist. The learning outcomes must be visible in the curriculum and the course evaluation criterion must include the desired learning outcomes. This facilitates the recognition of earlier know-how. The curriculum is the tool for the implementation of the learning and it contains the know-how areas based on the needs of work-life. The role of the teacher is to mentor and support the learning and in addition, help in the recognition of earlier know-how (Kangastie and Mastosaari, 2016b; Alaniska et al., 2019).

When the same kinds of problems and phenomena are dealt with during studies that occur in work-life, the students possess better capabilities to develop into experts and therefore improve their employment opportunities (Savander-Ranne et al., 2013; Kangastie and Mastosaari, 2016a). When looking at engineering education and the demands set by work-life, the implementation of the education must be arranged properly. The implementation requires anticipation, planning and organized work in order to achieve a functional structure for the education. One key factor in this is the academic curriculum work performed in HEIs. Curriculum can be seen as many things, but when looking at it as an organizing tool, it presents the yearly semester structure including all of the courses. This means that curriculum is a planning tool for education (Karjalainen et al., 2007). Based on the experience of the author of this thesis as the main responsible person in the Lapland UAS mechanical engineering degree program curriculum renewal project in 2014-2017, curriculum describes and defines the required technical expertise which is always involved in the discussion with work-life representatives. It can be stated that the work-life in Finland regarding the education of engineers is very active in setting demands for the education. This can be seen in student internships, for instance. The industry requires certain expertise in order for them to employ students during and after their studies. This means that the curriculum must be based on these needs and be actively updated to match the development of the general technological level. This sets demands for academic curriculum work but with active interaction with work-life, the results from the education are beneficial for the students and companies employing them. When looking at the meaning of curriculum deeper, it indicates the know-how the students achieve when courses have been passed with acceptable grade. In addition, the know-how can be regarded as perceptions the student forms from learning in different circumstances (Kangastie and Mastosaari, 2016b; Karjalainen et al., 2007). This concept of perception plays an important role in this thesis as P5 deals with the students´ perspectives on learning multiple AM technologies simultaneously giving one outcome to this thesis. The curriculum creation process is not standardized worldwide but nationally (e.g. universities and universities of applied sciences in Finland) use different recommendations for curriculum structure. Figure 5 presents a simplified curriculum process which forms an important background for this thesis.

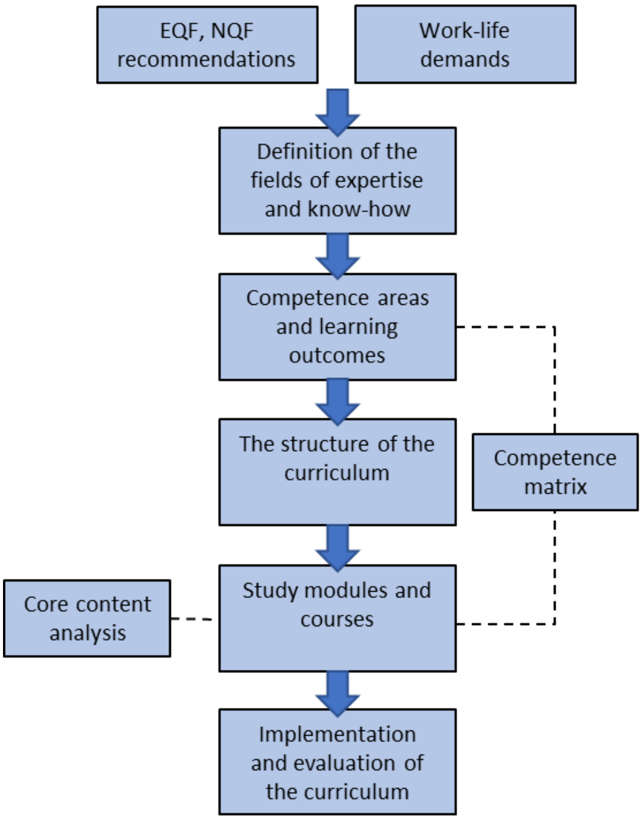


Figure 5. Curriculum process (applied from Karjalainen et al., 2007; Lapland UAS, 2015; Auvinen et al., 2010; Arene, 2007).

As seen in Figure 5, the origin of the curriculum work in Finland is in the European Qualifications Framework (EQF) which aims to unify the curriculums in Europe; the framework is developed by the EU. This facilitates the comparison of the acquired know-how between different countries. The National Qualifications Framework (NQF) defines the national structure for the degrees based on the EQF (Karjalainen et al., 2007). When looking at engineering education, demands set by work-life are in the background of the curriculum work, since one main responsibility of universities and especially the universities of applied sciences is to educate professionals according to the needs of work-life (Finlex, 2014). From this, the field of expertise of the degree is defined (when a new degree is designed) or checked (when the curriculum is updated or checked). This sets the direction of the degree (e.g. in mechanical engineering the focus could be on material sciences, product development and industrial engineering and the professional competence areas are built around these). The basic content of the teaching comes from the defined learning outcomes. Learning outcome describes the know-how the student achieves after passing a certain course. It helps to identify the expertise of the students and in addition, to evaluate the outcome for learning. Learning outcomes are defined through the EQF and NQF recommendations, work-life demands and nature of the degree (Honkala et al., 2009). Learning outcomes form the competence areas which help to classify the learning outcomes according to a certain topic. When the structure for the curriculum has been defined, the study modules and courses are defined and matched with the learning outcomes. This happens by connecting courses to the competence areas and learning outcomes. This is a helpful phase of the process which shows the building of the students´ know-how and expertise during their degree. Core content analysis defines the detailed knowledge and skills to be implemented in a course. This happens by connecting the learning outcomes to the core information that is presented in a course. The analysis happens usually by dividing the targeted know-how to categories (e.g. “must know”, “should-know” and “nice-to know”) (Karjalainen et al., 2007; Lapland UAS, 2015). During the implementation of the curriculum, continuous observation of the quality and functionality of the curriculum is essential in order to be able to evaluate and develop the curriculum (Karjalainen et al., 2007).

When looking at the situation of AM education with relation to curriculum and learning outcomes, research performed in this thesis indicate that the information related to these in the current literature is scattered. The need for the arrangement of AM education in the curriculum level has been mentioned in the literature (e.g. Mehta and Bernadier, 2019; Alabi et al., 2019; Ford and Minshall, 2019; Borgianni et al., 2019) but a clear plan and content for AM curriculum and learning outcomes is missing. This presents a gap in the current study. Figure 6 presents literature finding from Scopus regarding the combination of essential keywords. The keywords were as follows:

- additive manufacturing
- 3D printing
- pedagogy
- curriculum
- learning outcome

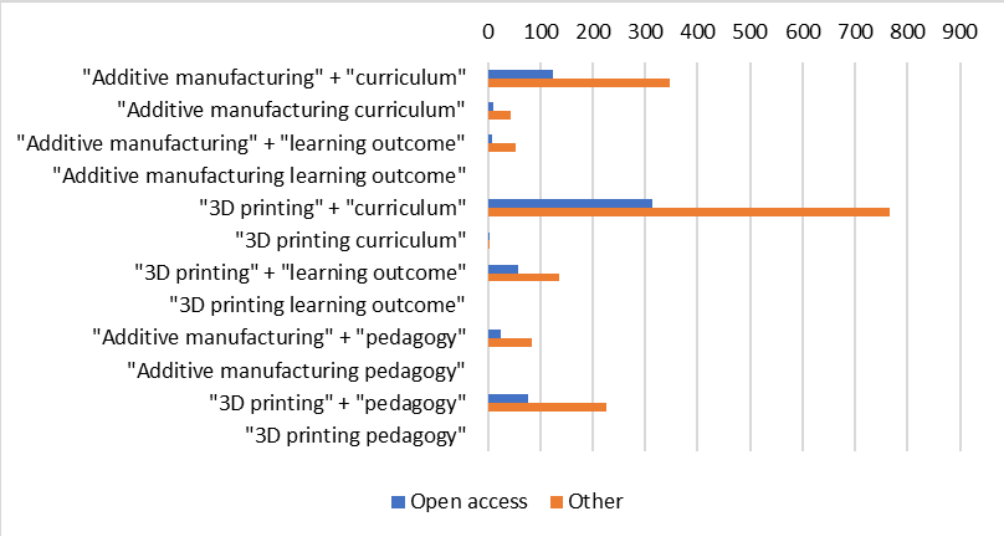


Figure 6. SCOPUS search results (SCOPUS Preview, 2021).

As seen in Figure 6, the combination of "additive manufacturing" + "curriculum" and "3d printing" + "curriculum" gave the most hits. When the search results were investigated closely, it can be noted that a majority of the results referred to the presentation of different AM projects and courses and in addition, to the students´ views of the learning outcomes. In this context the "learning outcome" referred to the students´ results from learning, not to the actual learning outcomes based on competences that are needed in curriculum planning work. When the search string was changed into "additive manufacturing curriculum" or "3D printing curriculum", the results decreased significantly. This is a matter of presentation of the search factors related to the article keywords. In many articles, these words were not involved in the article keyword listing and the SCOPUS search engine matched the article based on to the word matches, e.g. from the reference listing at the end of the article.

In addition, many results involved, e.g. K-12 science, technology, engineering and mathematics education (STEM) or primary school education related to 3D printing and this was not taken into consideration in this study. The search combinations "additive manufacturing" + "learning outcome", "3D printing" + "learning outcome" gave no clear result referring to the creation of learning outcomes needed in curriculum work. When connecting the word "pedagogy" to the search, the results indicated that there is no clear view presented to pedagogical fundamentals of AM education. Some articles dealt with the need for an AM educational framework but even in these, a clear plan for AM-based curriculum work or learning outcomes was missing. Based on the literature review and findings from in this thesis, it can be noted that this presents the need for this kind on study where the pedagogical fundamentals of AM learning are investigated and practical arrangements regarding curriculum planning are made.

One important factor in implementing curriculum in engineering is the arrangement of education in practical environments. Learning environments are places where the student can study phenomena and problems and form an understanding of the nature of the studied topic. The studied topic requires certain knowledge and skill sets and the learning environment is a place where this kind of application is supported. The student is encouraged even to question and evaluate the available knowledge (Kumpulainen et al., 2010). Learning environments should be safe environments where the needs of an individual student are met and the learning process is supported with calm working surroundings and safety (Finlex, 2012).

When looking at the learning environments in engineering education, the connection to work-life is important. Learning environments can be situated within (laboratories, classrooms etc.) or outside (internships at workplaces etc.) the educational unit. The common factor is that no matter the location, the learning should include elements from real life with real life problems, tasks and phenomena. The work-life elements in a learning environment (including internships outside the educational unit) increase the professional expertise of a student enabling the development of deeper problems solving skills, the ability to understand the learning process better and the ability to apply information. By solving actual problems connected to work-life situations, student motivation to study and learn increases. Therefore, the learning environment should contain elements from actual situations from work-life (Savander-Ranne et al., 2013). When creating a learning environment in engineering education, Figure 7 presents an example of the creation process helping to communicate which factors are necessary (applied from Savander-Ranne et al., 2013).

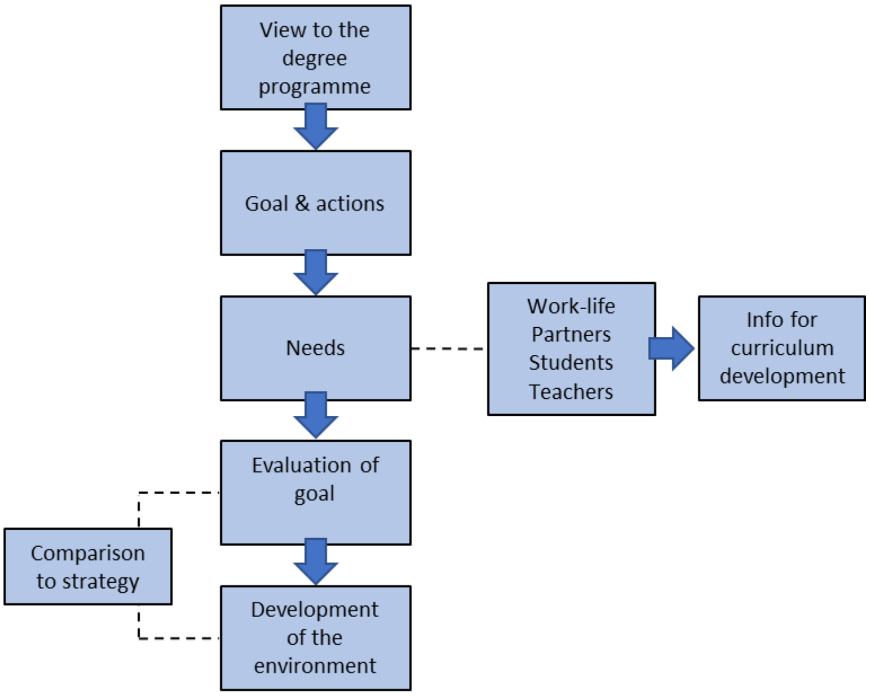


Figure 7. Elements and process for learning environment (Applied from Savander-Ranne, 2013).

As seen in Figure 7, the origin for creating a learning environment starts with the evaluation of the degree program contents. This gives information related to previous experiences and similar projects. Based on this, the goal for the development work can be to set and design all the necessary actions and steps to be taken in the process. Work-life needs are usually mapped through a questionnaire or discussion. In addition, this phase includes continuous discussion with stakeholders, partners, students and teachers in order to receive valuable insights for the development work. This phase gives information for curriculum development as the needs form a desired learning outcome for the education (Savander-Ranne et al., 2013; Pikkarainen, Piili and Salminen, 2020). The original goal is then evaluated with relation to the arrangement of the education (e.g. projects) in order to acquire information related to possible problems regarding the operation in the environment. The last phase is the actual implementation of the learning environment which usually happens within the degree program. This includes the actual development of the environment and operational and physical implementation. The development work in the last phases is evaluated through self-assessment and compared to the strategy of the university (Savander-Ranne et al., 2013).

## 2.3 Learning additive manufacturing

Additive manufacturing offers a versatile way to learn technology. The adoption of AM skills at different academic levels is the path to adopt AM into the manufacturing industry and even change the nature of modern manufacturing as AM offers new ways of manufacturing. The implementation of AM, especially in B.Sc. and M.Sc. levels of engineering, has a positive effect on the development of product development and manufacturing in the manufacturing industry. This originates from the increased innovation capacity and trained workforce through the arrangement of proper AM education (Mehta and Bernadier, 2019). When looking at the adoption of AM into the manufacturing industry, the common challenge is having a workforce with sufficient AM competence and the qualification to use AM machines. This presents the need for an academic framework where the AM skills are planted and grown, starting even from the earlier levels of education. This leads to skilled professionals who are able to understand the possibilities and limitations of the technology (Lloyd´s Register Foundation, 2016). There is a lot of so-called “general knowledge of AM” but in many cases, the in-depth knowledge is missing. The inclusion of AM skills in the learning processes, such as curricula development, is still progressing slowly in the academic world. One reason for this is that conventional subtractive manufacturing methods belong to everyday life since their history reaches many decades back. AM started to develop properly only about 20 years ago and the production of the knowledge (publications, books etc.) even later (Monzon et al., 2019). When looking at the AM education at the HEI level, the university level can be considered as one path to a competent workforce (Duchêne et al., 2016; Lloyd´s Register Foundation, 2016; Ford and Minshall, 2019).

AM is used in many HEIs as a method of bringing virtual 3D models into reality. This kind of learning where a digital 3D model is brought to reality enhances the learning of technical skills when the object can be visualized and perceived (Verner and Merksamer, 2015). Ford et al. (2019) published research where 280 different articles were investigated in order to map the use of AM in different education circumstances. One key conclusion was that the adoption of AM into learning was the most advanced especially in university engineering degrees. AM was seen as an important factor in engaging students into learning technical subjects. When looking at AM education in more detail, in order to create more advanced surroundings for learning, certain factors must be considered. First, the whole manufacturing process of a part must be put into a wider perspective where economic and technical aspects are considered. This refers to the fact that AM should not be used only as an individual method for implementing technology and be kept separate from the general context. The learner (the term student is used from here on in this study) must know the necessary background theory such as design principles and basics of the technology. In addition, the understanding of the phases of the AM process is important. This way the student can investigate the special characteristics of each phase. In the learning process, the AM ideology must be put into a context of use applications giving meaning to the technology (Kircheim et al. 2017).

When looking at AM from the knowledge and education point of view, Duchêne et al. (2016) released a report conducted by the European commission based on case studies in different areas in Europe (e.g. airplane industry, surgical planning and machine spare part production). Certain policy implications were investigated and presented in the report in order to improve the distribution of AM in Europe. This was conducted by identifying application areas, missing competences, barriers and opportunities in order to decrease and defeat the obstacles in the deployment of AM. Figure 8 presents the collected policy implications referring to knowledge and education (applied from Duchêne et al., 2016).

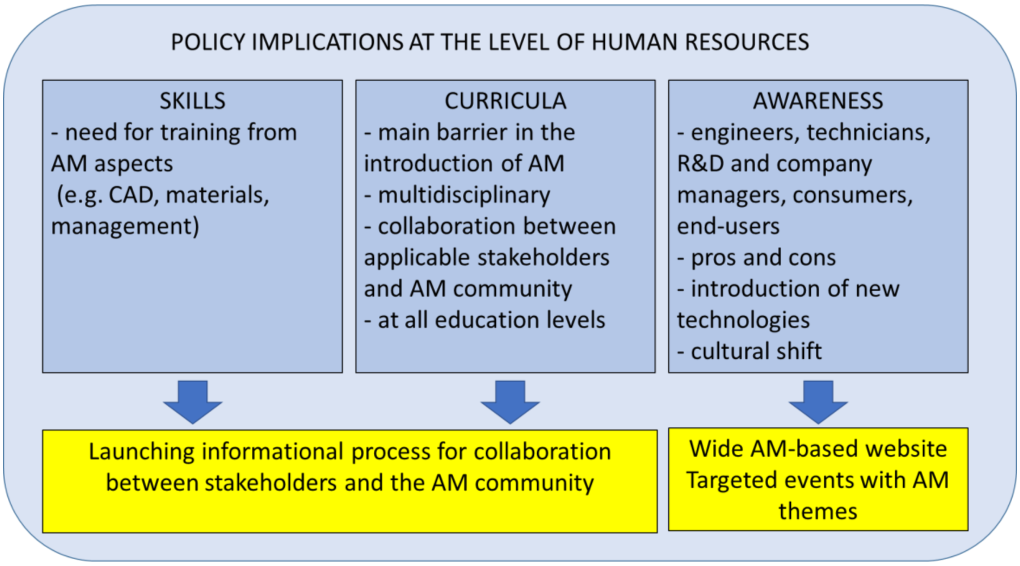


Figure 8. Policy implications concerning education (Applied from Duchêne et al., 2016).

As seen in Figure 8, the three factors related to human resources; skills, curricula and awareness are connected to the main motivation of this thesis as presented in Chapter 1.1 of this thesis. The skills refer to the need for arranging training and education for AM-related topics and aspects as presented in Figure 8. Curricula development in all education levels was seen as the main issue to be dealt with when overcoming obstacles in the deployment of AM in different areas. The insufficient amount of knowledge and economic and social issues were highlighted as barriers for the deployment of AM in Europe. One presented solution for this is to a launch process for collaboration between stakeholders and the AM community which aims toward the distribution of knowledge. In this, the educational sector (e.g. engineering universities) play a major role especially through curriculum development (Pikkarainen and Piili, 2020). The use of 3D printing in model manufacturing is increasing, especially in training, but the awareness related to AM is still insufficient. The promotion of information for different professional users (e.g. engineers, research and development (R&D) managers) and sharing information between operators (e.g. professionals in certain area, companies and AM actors) raises awareness related to the possibilities of AM. A presented solution for this is the creation of a website dealing with AM issues in Europe and world-wide. The arrangement of events with an AM theme targeted to certain user groups helps to increase AM awareness (Duchêne et al., 2016).

The learning of AM is usually connected to practical circumstances where the digital 3D model is brought to reality with AM. The origin of the practical work is often connected to a certain task or problem and this presents different implementation ways for the learning of AM. Learning AM requires different methods since AM presents different situations where problems must be solved and the knowledge level of the students affects to learning. AM education needs a proper environment in which the learning can happen in situ. The typical environment is an AM laboratory where the practical learning of AM takes place. The information of arranging AM education in this kind of environment is scarce in the current literature (Pikkarainen, Piili and Salminen, 2020). Usually this kind of laboratory serves a certain purpose and contains AM equipment. There must be the possibility for student groups to work side by side and technical assistance for the management of AM machines must be available (Harvey, 2016). The current literature does not contain clear information on how an AM learning environment should be implemented (as presented in P2) and this emphasizes the importance of this study. Chapter 2.4 presents examples and typical methods for how AM is implemented at university and university of applied sciences level regarding the nature of requirements for AM learning.

## 2.4 Learning methods and concepts for AM education

The nature of AM learning is a combination of theoretical aspects and practical work as in many other manufacturing methods such as turning or milling. This includes laying the theoretical foundation in AM courses and the adaption of acquired knowledge into practice through practical AM projects and exercises. The benefit of using AM in education is the fact that the equipment can be used in classroom environments (e.g. desktop-type printers) and it offers a versatile way to combine theory and practise. The following presents suitable learning methods to be applied in the learning of AM. The methods can be combined within an AM learning environment where students work in different phases such as acquiring theoretical information, designing a 3D printable model or working with a 3D printer implementing a printing task.

*Problem-based learning (PBL)* is an approach where theoretical issues are connected with solving an existing problem. The nature of the problem is usually of relevance to the topic to be learnt and the learning is centred around the problem-solving process (Askehave et al. 2015). In addition, the problem can be a phenomenon connected to a work-life situation. PBL contains two parts as presented in Figure 9.

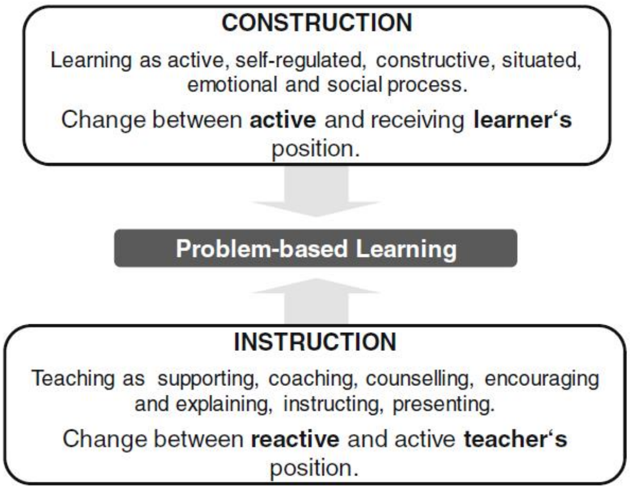


Figure 9. Problem-based learning (Seidel and Schätz, 2019).

As seen in Figure 9, in *construction,* the student is responsible for his/her learning through self-activation. Regarding the learning of AM, this includes the independent acquisition of knowledge where the student takes responsibility for his/her own learning. In *instruction,* the learning is based on reactivity where the student receives teaching and support in the problem solving. The role of the teacher can be seen as a mentor or guide in the process (Seidel and Schätz, 2019). The problem-solving process is divided into phases and the process itself can appear to be more fruitful for learning than just reaching the solution (Kangastie and Mastosaari, 2016b). Problem-solving is a process where the learner combines different self-aware levels of knowledge such as cognitive and metacognitive processes. The learning situation enhances the learner's awareness to use his/her own knowledge and construct a suitable solution to a problem (Karyotaki and Drigasm, 2016). These problem-solving skills are valuable in engineering where the situation is usually connected to a certain technology (in engineering education, many learning occasions include the use of equipment or technology, AM is one good example from this). Traditional lecturing is not the most suitable method for teaching AM topics. Each student is an individual with their own perspectives to learning and therefore, e.g., the teaching of AM design principles cannot be done as a package given at the same time for an entire group of students. The students must be introduced to real problems in order to be able to create solutions based on earlier adopted knowledge related to AM with the guidance of an instructor. The role of the instructor (usually the teacher) is to mentor the student through the problem-solving process. AM presents many topics for PBL such as evaluating the outcome from a printing task and evaluating possible errors in the printing process. This requires the combination of areas such as metrology into the analysis of the part and the reflection on the design process (Williams and Seepersad, 2012). PBL supports the combination of theory and practice and especially the development of self-awareness related to the nature of AM. This is a key element when looking at the training of AM experts who are able to define and analyse problems related to AM and gain knowledge and experience based on PBL process (Kircheim et al., 2017). Based on the experience of the author of his thesis, PBL provides an excellent method for arranging AM education since AM provides many situations where problems occur (e.g. insufficient adhesion of the part to the build platform in material extrusion) and need to be solved. The student must first analyse the nature of the problem to be aware of the factors affecting to the problem. The problem-solving is phased where all the factors (e.g. build plate condition and printing variables such as temperature) are investigated in order to find the root of the fault. Even though the problem-solving process is independent, the teacher acts as a mentor by giving directions for the problem-solving process.

*Project-based learning (PjBL)* is a learning method where the learning activity is seen as a long-term process where the problem solving includes interaction and collaboration with others. Problem solving is usually seen as an event where learning activities are scattered and not connected to any certain context. PjBL promotes the importance of the process where the learner reflects, applies and evaluates his/her own experiences and knowledge with respect to problem solving. This leads to a deeper understanding of the learning outcomes compared to separated and individual problem-solving cases where no evaluation or deeper thinking takes place. Physical environments such as laboratories and other learning environments are good places to implement project-based learning, as they support practical learning with project topics (Gary, 2016). In addition, PjBL can be seen as hands-on learning of AM where the learning project (e.g. designing of light-weight AM structures) occurs in phases which enables progressive learning. Progressive learning refers to the development of learning where experience increases as the learning process progresses. The AM process works with different phases so by separating phases of the project, the student is able to conceive the learning outcome better (Yang, 2019). The nature of PjBL is at its best in group work where the collaboration takes place when identifying solutions to problems. When multiple groups work with the same topic, the outputs can then be compared from different perspectives (Williams and Seepersad, 2012). In addition, PjBL presents the possibility to connect the learning project into a competition where student groups can compete with each other. This has been noted to increase motivation and self-engagement in learning AM topics (Yang, 2019). Based on the experience of the author of this thesis, PjBL does not have to be viewed as a separate learning method as it can be included in the PBL process. Regarding the learning of AM, the learning takes place usually in an AM laboratory where the learning is centred on projects which then can be implemented through PBL methods.

*Literature review-based learning (LrBL)* is a method where the student studies literature from a selected topic, performs a presentation on the topic and writes an essay or paper. These will be evaluated and reviewed. A lecture from the topic usually precedes the LrBL process, giving the student sufficient background from the topic for successful implementation of the review. This method is proven to give the student deeper theoretical knowledge related to AM technologies and fundamentals as the research and writing skills improve at the same time (Yang, 2019). Based on the experience of the author of this thesis, LrBL can be seen as one method for providing theoretical information. One example of this is the learning assignments as presented in P1 where in the first phase of the assignment, the student must build a learning portfolio for certain AM topics in order to be able to proceed to the practical AM exercises. The student must present the portfolio to the teacher and through mutual discussion, the student receives feedback related to their level of achieved theoretical learning. When looking at the current situation with the COVID-19 pandemic, LrBL presents a good way to learn theoretical topics independently as the necessary lectures and literature work can be done as distance learning.

*Cooperative learning (CL)* is often connected to PBL but when looking at it individually as a learning method, it emphasizes the importance of team work. The group of students have a common goal (usually solving a certain problem) and each individual has equal responsibility for the success of the task. Therefore, so-called “shared responsibility” is usually not one person´s responsibility and each student have their own share of responsibility to fulfil related to the other students. This kind of learning promotes interaction where the information can be shared in parallel; the students can help and teach each other. When sharing tasks as a team, the project-work skill develops as the team must distribute tasks and define a timetable. As the learning progresses, the students must evaluate their own output and this develops their self-assessment skills through reflection (Rüütmann, 2009). Based on the experience of the author, the AM projects performed in groups offer a versatile way to learn. The level of know-how varies within the groups and through CL, the students can also educate each other. CL does not have to be viewed as an individual learning method since it usually is connected to many learning methods such as PBL but still it is important to recognize the value of CL in the learning of an individual student.

The methods (PBL, PjBL, LrBL and CL) form the description of tools which can be used as practical methods in AM teaching. When looking at the AM learning in detail, concepts of *situated learning, practice-oriented learning* and *perceived learning* must be discussed. These concepts are used in this thesis to describe and understand the learning process of AM and form the framework enabling the use of PBL, PjBL, LrBL and CL in AM education. *Situated learning* refers to learning in different environments and settings through knowledge distribution. The principle of the concept is presented in Figure 10.

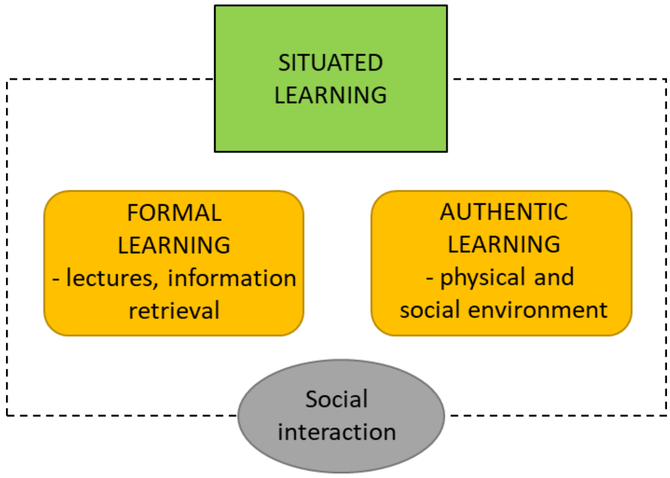


Figure 10. Concept of situated learning (Pikkarainen, Piili and Salminen, 2021b).

As seen in Figure 10, *situated learning* contains two main elements: formal learning and authentic learning. Formal learning refers to the more traditional ways to learn such as through lectures of independent acquisition of knowledge. This lays the theoretical foundation for the topic at hand by giving the student required informational background. Authentic learning includes the places and environments where the learning takes place (e.g. in AM laboratory). The concept includes the element of social interaction where the students interact with each other (e.g. in project works where the work is usually done in groups) (Besar, 2018; Handley et al., 2007).

The concept of *practice-oriented learning* refers to learning where the requirements and needs of work-life are applied in practical situations. The principle of the concept can be seen in Figure 11.

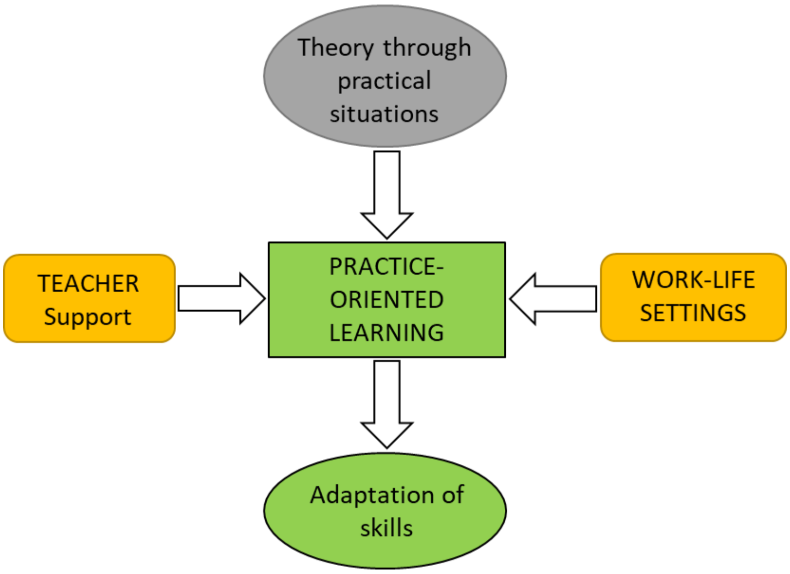


Figure 11. The concept of practice-oriented learning (Pikkarainen, Piili and Salminen, 2021b).

As seen in Figure 11, the learning is based of work-life settings which provide the framework for learning. This manifests in practical learning situations where the learning is organized to reflect work-life. Situations such as projects with topics from work-life or student internships provide the possibility to apply acquired information in a real context. This resembles the authentic learning in *situated learning* but in this concept, the learning is supported and mentored by a teacher and as an outcome, the learning produces the adaptation of skills needed in work-life. Theoretical information is a prerequisite for this concept in order to apply it in practical situations, but it is not included in the concept (Smirnova et al., 2019; Chuchalin and Vyuzhanina, 2014; Whelan et al., 2016, Abykanova et al., 2017). *Perceived learning* focuses on the students´ perception from the learning and can be viewed as the output from the learning process. The principle of the concept can be seen in Figure 12.

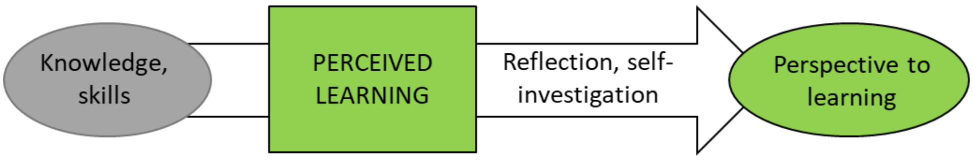


Figure 12. The concept of perceived learning (Pikkarainen, Piili and Salminen, 2021b).

As seen in Figure 12, the processing of knowledge and skills includes reflection and self-investigation in order to form a perspective to the learning. This refers to the measurement of the students´ perception from the learning which is usually performed through self-evaluation or reflection (one method for this is to arrange a questionnaire where the opinions and feedback from the learning and teaching are collected) (Bacon, 2016; Zhang, 2016; Suhoyo et al., 2017; Möller and Shoshan, 2019). This enables deeper analysis of the learning result and can be used as a method for developing the educational contents. This is one important factor for this thesis as P5 discusses the perspectives of mechanical engineering students regarding learning AM with multiple AM technologies.

## 2.5 Knowledge transfer

The key factor in transferring AM knowledge is the collaboration between the universities and companies/industrial actors aiming to connect the intellectual functions (e.g. academic research and development) of universities, industry and research institutions. In this thesis, AM knowledge refers to the output of learning AM in engineering. Motivation for collaboration is one key issue. Companies´ research needs are usually based on economic growth and new business opportunities. This sets demands for the collaboration as the companies usually drive for research topics with low risk levels and the possibility for near-future launch (Tunca and Kanat, 2019). The transfer of information is a two-way path where universities transfer knowledge to industry (U-I) or from industry to university (I-U). In the context of this thesis, the term “university” refers also to universities of applied sciences. The role of universities is the provider of academic knowledge and research, whereas the role of universities of applied sciences is concentrated more on the education of work-life professionals. The nature of U-I and I-U is presented in Figure 13. The term “industry” is used in the literature but it refers also to companies and other work-life partners.

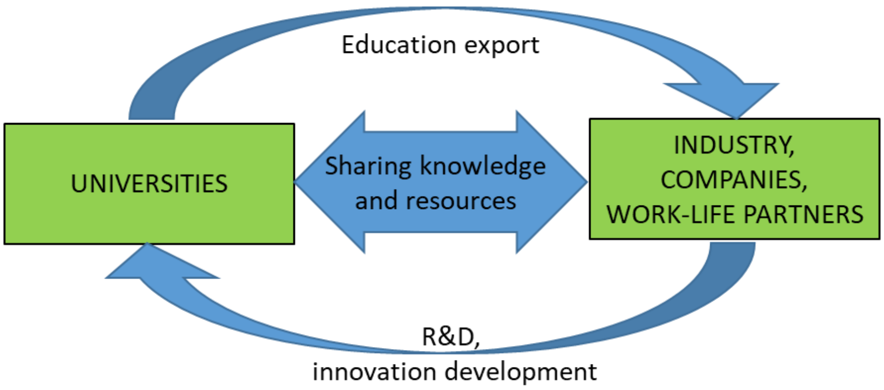


Figure 13. Relationship between universities and industry/companies (Applied from Shi et al., 2019; Borah et al., 2020; Steinmo and Rasmussen, 2018; Liu et al., 2020; Guerrero, 2020).

As seen in Figure 13, U-I collaboration refers to functions where the innovation capacity of companies is supported through, e.g. education export (teaching, training courses, etc.) by creating a network covering knowledge sharing and resources with cross-innovation and common goals (Shi et al., 2019; Borah et al., 2020; Steinmo and Rasmussen, 2018). This kind of collaboration increases the possibilities for the company to enhance the competitiveness and drive for increased profitability, although the current literature does not give a clear view of how the actual enhancement (e.g. building social capital and innovation readiness) occurs in companies. This is seen as a driving element for the knowledge transfer between universities and companies (Steinmo and Rasmussen, 2018). I-U refers to collaboration where companies seek support for their R&D and innovation development functions from HEIs (Liu et al., 2020). This includes different activities related to development of technology or innovation work which are supported by industrial actors, universities and different research institutions. This kind of operation is usually funded and supported by different quarters such as the government or scientific institutions. In addition, I-U functions can be seen as a way the industry influences education through an input (Song et al., 2020; Borah et al., 2020). One important part of the I-U collaboration is the employment of graduated students in companies which is also one method of knowledge transfer (Guerrero, 2020; Borah et al., 2020).

The most important challenge in the adoption of AM is the efficient transfer of information and knowledge from universities and other educational units into the manufacturing industry and companies. The two main issues to be dealt with are the concept of knowledge transfer and the collaboration between universities and the industry. AM technologies are a promising way for companies to increase their productivity and be competitive, but the technologies are still used by a quite narrow group of users. The need for increasing AM-related knowledge is clear. The low-cost side of certain AM technologies (e.g. material extrusion) has made it very popular in universities, universities of applied sciences and other educational units. This has caused a situation where the popularity of AM has led to resources being directed to the educational sector, to students and scientists and not to companies. In some cases, technological development moves even faster than knowledge; many AM educational information sources (e.g. books) rapidly become outdated. The production of AM knowledge requires more updating than any other field of manufacturing today. Developing courses and material in universities, especially curricula for the B.Sc. and M.Sc. levels, is important since these levels produce the professionals for industry and different academic sectors such as research. Different training modules and programs, courses, seminars and educational books need to be developed and distributed into the academic communities (Monzon et al., 2019). Knowledge transfer can be seen as a process where the knowledge produced in HEIs ultimately leads to changes in society through companies. The concept of knowledge transfer has been discussed in the literature but when the education point of view is implemented in the process a separate model must be created in order to understand better the need for AM education. This was one of the main motivations for P2 which deals with the concept of knowledge transfer.

# 3 Methodology

The methodology of this thesis is presented in five publications published in scientific journals. Each publication contributed state-of-the-art views to the AM-related literature and the work is based on the arrangement of AM education of the Lapland UAS mechanical engineering degree program, providing the testing of the methods of this thesis in courses over the years. This gave practical know-how related to the arrangement of AM education. The background for the presented methodology is derived from the 14 years of experience of the author of this thesis as a teacher in the field of mechanical engineering. This enabled the reflection of the pedagogical methods presented in this thesis leading to the results as presented in P1-P5. One main factor in this was the mechanical engineering curriculum renewal project in 2014-2017, where the author acted as the main responsible person in the development work. The project included training and education from curriculum structure and planning and it gave the necessary theoretical know-how for this thesis when looking at the development of AM-based curriculum and learning outcomes. The following presents the methods from each publication.

## 3.1 P1 methodology

The first publication provided the background for this thesis. The methods of P1 were based on empirical studies when arranging the foundation for AM education. This included the acquisition of the first AM equipment and their use in engineering courses. The empirical studies were supported by literature review and collaboration between the Lapland UAS mechanical engineering degree program and LUT University research group of laser materials processing and additive manufacturing.

## 3.2 P2 methodology

The methodology of P2 was based on state-of-the-art literature related to the pedagogical elements of AM learning and the need for improved knowledge transfer principles for AM. This required the detailed identification of the knowledge transfer elements together with the elements of AM learning. These were included in curriculum development work which gave the platform for the pedagogical development work. This was the origin of *technical pedagogy*, which gave the description for the AM pedagogy based on technical perspectives. The development of the pedagogy started by identifying the necessary factors for the model as presented in Figure 14.

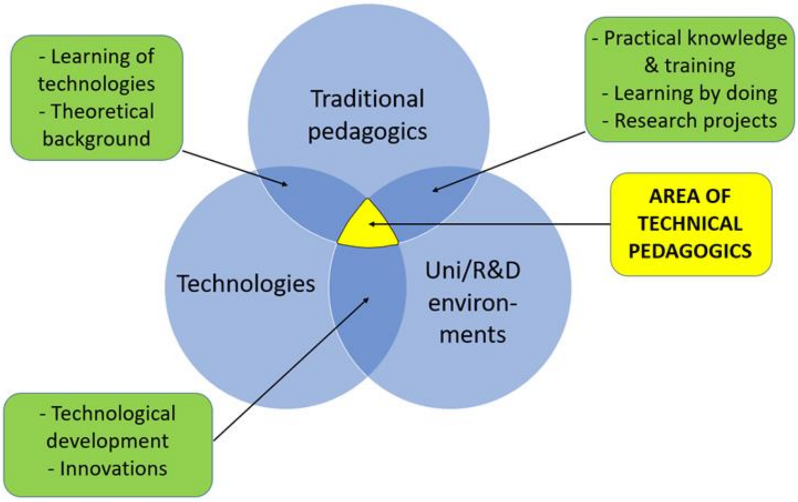


Figure 14. Foundation for technical pedagogy (Pikkarainen and Piili, 2020).

As seen in Figure 14, the foundations for the model were the elements from traditional pedagogy, technological aspects and the educational environment being the university and its R&D functions. These elements were viewed as circles overlapping each other. These overlapping areas presented functions enabled by the areas. Pedagogics and technologies form the base for learning the technologies together with the theoretical background. Technologies and the educational environment form technological development, with innovations being an important area when looking at the AM research performed in universities. Pedagogics and the educational environment form practical knowledge and training, learning by doing aspects and student research projects. This area is more student-centred enabling the practical arrangement of AM education. When all of these areas are viewed together, the area of *technical pedagogy* can be found at centre of it all.

## 3.3 P3 methodology

The methodology of P3 was based on literature review and the design process of an occupationally safe and functional AM laboratory. The research was based on a process for designing an AM laboratory which was used as a method in the actual development of a new AM laboratory. The process is presented in Figure 15.

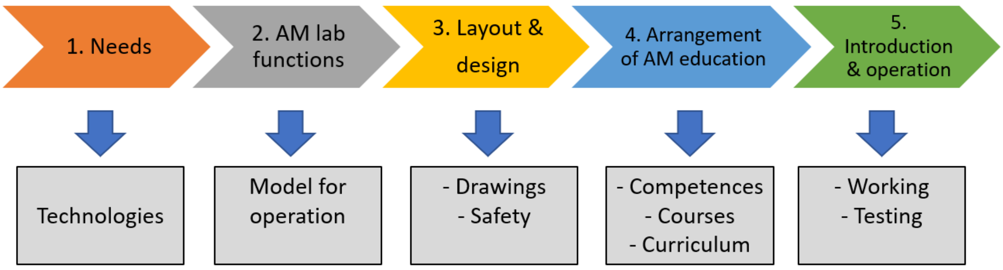


Figure 15. The design process of the AM laboratory (Pikkarainen, Piili and Salminen, 2020).

As seen in Figure 15, P3 was based on the design of the AM laboratory. The process started from the need to arrange AM education which defined the used technologies. This led to planning of the functions and operations for the laboratory including the theoretical study concerning the AM safety factors. The following stage included the practical design work of the laboratory. The design work included the layout, electrical, safety and ventilation design work. The design of the safety of the AM laboratory was based on the literature review presented in P3. The following phase was the actual arrangement of the AM education including the pedagogical planning. In the final stage the laboratory was introduced and the operations and functions of the laboratory were tested.

## 3.4 P4 methodology

The methodology of P4 was concentrated on the mapping of work-life requirements to the AM. A questionnaire was sent online to companies and industry representatives in northern Finland. The area was selected according to the Lapland UAS education area where a majority of the students are employed after graduation. The questionnaire was arranged with Webpopol software as presented in Appendix B.

The questionnaire was divided into numerical questions with the scale of 0 – 10 where zero presented the “not important” option. The value ten presented the “very important” option. The last question allowed the respondents give free-form responses about the required knowledge concerning know-how for future engineers. The total number of responses was 56 from the areas of machine and equipment production, product development, piping and metal and the pulp and paper industry. The responses were analysed and drafted into the form of learning objectives describing the required know-how. Figure 16 presents the process for creating the learning outcomes in P4.

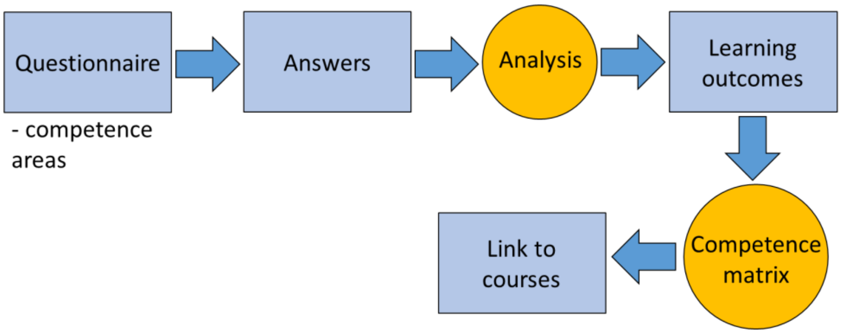


Figure 16. The creation process for the learning outcomes in P4.

As seen in Figure 16, the questions were referred to as competence areas, as presented in chapter 2.2. of this thesis, connected to different AM topics. The answers were analysed with quantitative and qualitative methods. The quantitative analysis of the answers was based on calculating the average from the responses concerning each question. Answers with a mean value over 8.0 were regarded as important and were emphasized in the study. The analysis included the qualitative viewing of the answers generating the learning outcomes. Bloom´s taxonomy was used in the categorization of the competence areas and learning outcomes. The learning outcomes were linked to the Blooms´ taxonomy categories according to their nature. If the learning outcome presented was more advanced (e.g. the requirement for analysis), it was located in the latter part of the taxonomy, hence the advanced learning. The learning outcomes were linked to the courses through the competence matrix. The matrix presents which competences areas are achieved in courses and it enables the planning of course contents in detail at the curriculum level.

In this thesis, learning outcome refers to the know-how the student achieves when passing a course with accepted grading. The categorization of the learning outcomes is presented in Figure 17.

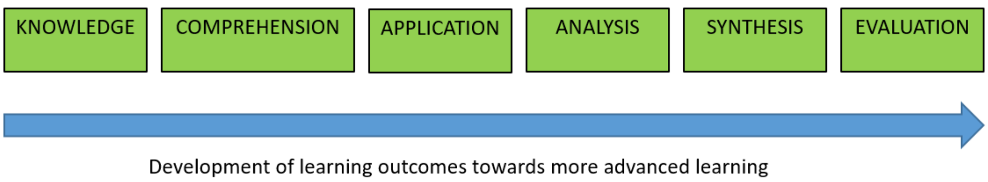


Figure 17. Learning outcome categories according to Bloom´s taxonomy (Pikkarainen, Piili and Salminen, 2021a).

As seen in Figure 17, the taxonomy consists of six categories guiding the study of P4. According to Bloom (1956) and Karpen and Welch (2016), in *knowledge*, the student acquires information and understands it. In *comprehension* the student understands the nature of the information and can explain phenomena based on the information. In *application*, the student is able to apply the information in different circumstances and in *analysis*, the student is able to analyse the nature of the problem. In *synthesis*, the student can combine ideas into solutions and in *evaluation,* the student is able to use cognitive thinking in evaluating actions or the generated solution to a problem. The learning outcomes are then placed in the categories based on the nature of them. The learning outcomes are described with verbs such as *"can"*, *"choose"*, *"interpret"* and *"adapt"*, just to mention a few. These categories can be seen as a path to advanced learning presenting the evolution of the students´ know-how.

## 3.5 P5 methodology

The methodology of P5 consisted of a questionnaire answered by Lapland UAS mechanical engineering students during an AM course called "3D Printing and applications" in 2020. Due to the COVID-19 pandemic, the course´s practical laboratory work had to be postponed and was then arranged as a part of another course, "Future Technology", in fall 2020 when the situation allowed the university to be open again. Even though the learning was divided into two courses, they are referred to as one course in this thesis. The goal for the course was to introduce the students to three AM technologies: material extrusion (FDM), vat photopolymerization (SLA) and powder bed fusion of polymers (SLS). First, the selection of these three technologies was based on the fact that they are the three most used AM technologies worldwide. Second, the experience from the theoretical background of AM presented the suitability of these technologies to educational purposes. This includes the possibility for students to use the selected technologies also independently. Third, the application and price range of these technologies was suitable for educational purposes. The course consisted of theoretical studies, design work and practical work with the printers implementing the concepts of situated learning and practice-oriented learning. The structure of the course is presented in Figure 18.

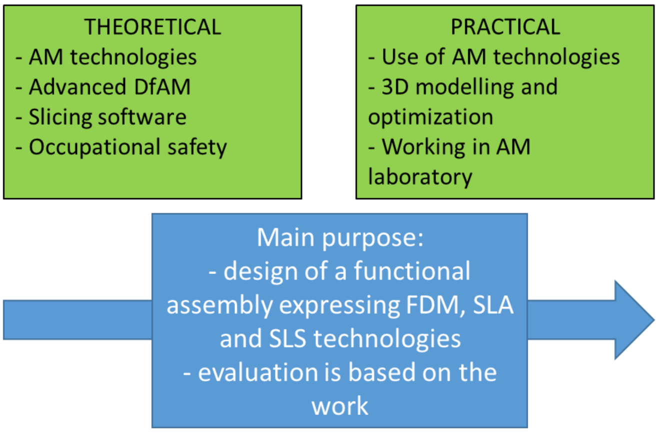


Figure 18. Structure of the AM course (Pikkarainen, Piili and Salminen, 2021b).

As seen in Figure 18, the main purpose of the course was to design an assembly expressing the characteristics of the three technologies. The students used the AM process selection model as presented in P4 in order to select the most suitable AM technology for each part. The goal was to learn and use multiple AM technologies simultaneously. The course evaluation was based on the assignment including all the phases of the work. The theoretical studies consisted of the presentation of the AM technologies and advanced DfAM principles including special design characteristics such as the effect of thermal energy between layers in SLS or exit holes for resin in SLA. In addition, it contained the presentation of the slicing software for SLA and SLS printers and occupational safety (e.g. the need for ventilation or the use of proper protective gear). The occupational safety information was based on the results from P3. The practical part of the course consisted of the presentation and use of the three AM technologies, 3D modelling and optimization and working in the laboratory (e.g. printing and post-processing). The students worked in the laboratory partially under supervision and partially independently as they had access to the laboratory outside the regular lectures. Access was supervised through personal key cards. The arrangement of the course followed the combination of learning methods and concepts as presented in P5. The learning outcomes for the course were derived from the results presented in P4 as presented in Figure 19.

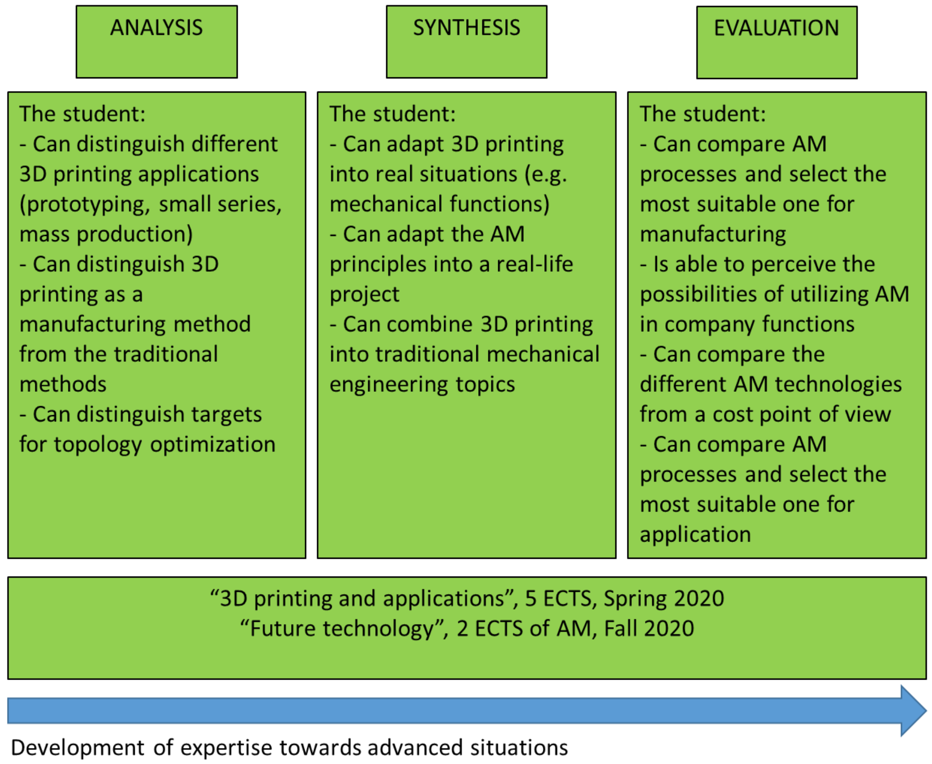


Figure 19. Learning outcomes for the course (applied from Pikkarainen, Piili and Salminen, 2021b).

As seen in Figure 19, the learning outcomes for the course are connected to the latter part of the Bloom´s taxonomy as the course is an advanced AM course. The course precedes AM courses and projects with a total of 20.5 ECTS, giving the students necessary basic information related to AM technologies. FDM technology is a part of these prior courses so the student possesses sufficient knowledge of it in order to deepen their knowledge in this advanced course.

The feedback from the course was collected online with Webpopol software as presented in Appendix C. The questionnaire was divided into numerical and free-form questions. The numerical questions were arranged with the scale of 0 – 10 where zero presented the options "minor", "failed", "weak" or "easy", depending of the question. The value of ten presented the options "major", "successful", "strong" or "difficult", depending on the question. The nature of the free form questions was meant to give a more detailed explanation and background to the numerical questions. In this section, the students could write freely response to the questions. The total number of responses was 14 due to the small size of the student group. Table 1 presents the free-form questions.

Table 1. Free-form questions (Pikkarainen, Piili and Salminen, 2021b).

| **Written questions** | **Free form answer** |
|---|---|
| 1. What is your experience using multiple 3D printing technologies simultaneously? | |
| 2. Does the simultaneous usage of multiple 3DP technologies strenghten / weaken the learning of 3DP? Justify your answer. | |
| 3. How did you feel about the development of your skills during the course (learning process)? | |
| 4. Did the AM process selection model help you in selecting the suitable technology for printing? (How ? Possible improvements?) | |
| 5. What did each technology (FDM, SLA, SLS) give to the learning of 3D printing? | |
| 6. What was the most difficult thing about learning and using the technologies (identify according to each technology)? | |
| 7. Suggestions for improving the course? | |
| 8. Free-word and general opinions | |

As seen in Table 1, the questions were targeted to give broader answers to the presented topics and to support the analysis based on the numerical questions concerning the learning experiences of students.

# 4 Results

This chapter presents the results of the thesis based on publications P1-P5. The following section presents the role of each publication in this thesis and especially their contribution to the whole. In addition, the following section presents the main findings from each publication. The results from the findings are summarized in the discussion chapter where they are compared to the bibliographical findings and research questions.

## 4.1 Publication I

### 4.1.1 Objective

The aim of P1 was to act as the starting point for the study of the arrangement of AM education. The goal was to create a conceptual learning environment for AM connecting the elements of AM and traditional engineering design process, more specifically the traditional product design (PD) process as developed by Ulrich and Eppinger (2008). This derived from the need to arrange AM education for mechanical engineering. The AM elements, as presented in this study, are the AM theoretical background, generic AM process, DfAM principles and required AM technologies. The traditional Ulrich and Eppinger (2008) PD process was used as a background for engineering design studies and there was a need to develop a new kind of product design process combining the AM into the traditional PD process. This was the starting point for the study and for the introduction of AM in the Lapland UAS mechanical engineering degree program. There was a need for identifying the pedagogical elements connected to AM education in engineering and P1 enabled the background for this doctoral thesis.

### 4.1.2 Results

The main results from the study were divided into practical and conceptual parts. The conceptual part combines the engineering design principle and AM. Concerning the practical side of AM, *the modified 3D printing process* was developed in order to introduce students to the use of the material extrusion printers as presented in Figure 20.

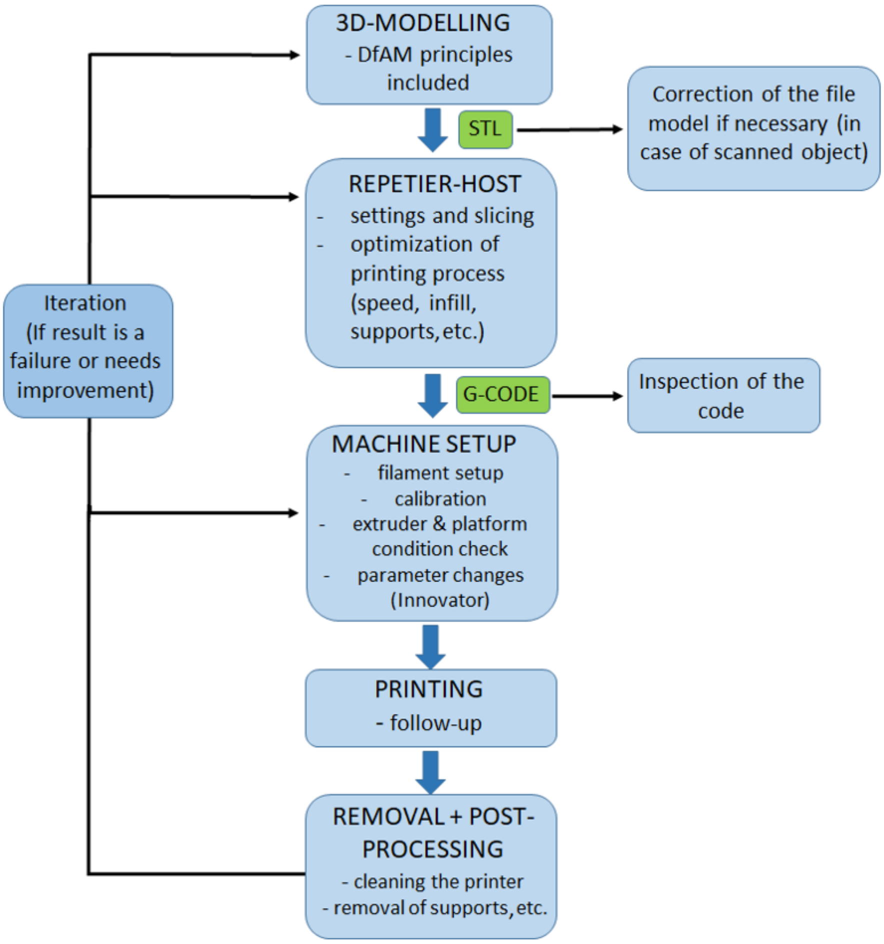


Figure 20. Modified AM process (Pikkarainen, Piili and Salminen, 2017).

As seen in Figure 20, the modified AM process was based on the generic AM process as presented by Gibson et al. (2021). This would facilitate the introduction and use of the printers with the modified process chart providing condensed information related to the AM process and printer use. The use of the model presented the need for applying it also to other AM technologies and the need for multiple AM technologies in order to develop proper AM education. This led to the study presented in P5 and was one of the starting points for this thesis when discussing the learning of multiple AM technologies.

Concerning the conceptual part of the study and the combination of engineering design and AM, *the new AM-based PD process* presents a new approach to the product design process. It was noticed that the Ulrich and Eppinger (2008) PD process could not be used directly for AM purposes and therefore the main author of P1, the author of this thesis decided to develop a new process to be more suitable for AM purposes. The new process is presented in Figure 21.

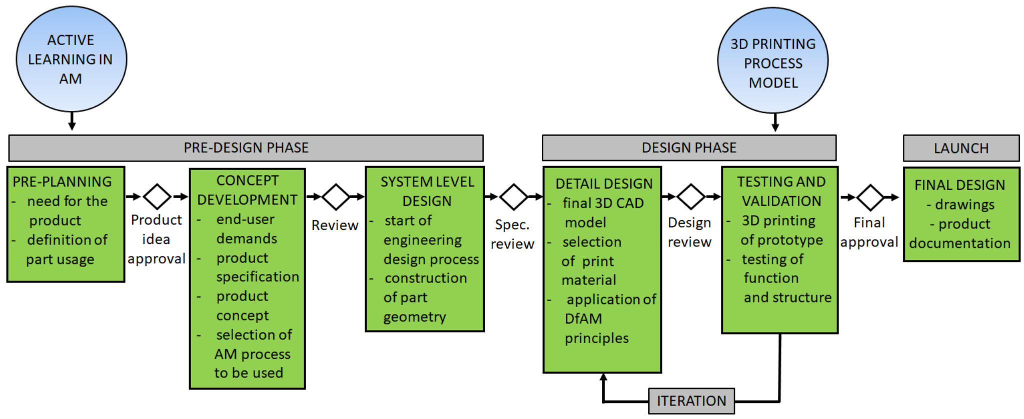


Figure 21. New AM-based PD process (Pikkarainen, Piili and Salminen, 2017).

As seen in Figure 21, the new process includes the description of active learning, which identifies the elements of learning such as acquiring background knowledge from AM, practical work with the AM equipment and time planning and use. This was the starting point for identifying the AM learning elements. The new process includes the simplified 3D printing process and the AM elements are embedded in the traditional PD process. The new process assists the students in the AM product design work and enables the reflection of the learning factors in the process. The new AM-based PD process was introduced to 3D printing courses as a guideline for the AM design work. The courses followed the Conceive-Design-Implement-Operate (CDIO) principle where the learning has been divided into four stages according to Crawley et al. (2014). The process of *conceive, design, implement and operate* has been proved to be a good learning process, especially in engineering sciences since the process emphasizes creativity and critical thinking. In this thesis, the CDIO principle was seen as a good method in implementing AM education as it was the official learning view of the Lapland UAS mechanical engineering degree program. The CDIO principle was applied through learning assignments as the principle divides learning into four consequential phases. The description of the *learning assignments* was created to be used in the 3D printing courses which divided the learning process into two parts. This would combine the practical and conceptual part together and form the foundation for the learning. The first part of the learning assignments is presented in Figure 22.

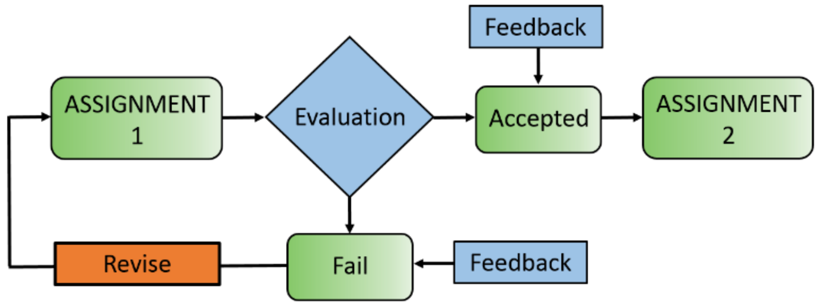


Figure 22. First part from the learning assignments (Pikkarainen, Piili and Salminen, 2017).

As seen in Figure 22, the first part from the learning assignments presents an iterative process where the student is introduced to the theoretical foundation of AM (AM technologies, generic AM process, DfAM, post-processing and the new AM-based PD model) through a written learning portfolio included in ASSIGNMENT 1. This presents the first phase of the CDIO process (conceive) where the students acquire the foundation for the phenomenon by introducing themselves to the subject. Introduction lectures, flipped learning and LrBL are used as learning methods in this phase. The student investigates the information independently by writing a learning portfolio based on the topic. The portfolio is then presented to a teacher and through discussion, the student receives feedback and possible information on how to revise the portfolio in order for it to be accepted. When the portfolio is accepted, the student can proceed to the second assignment. This first part works as “a driving licence” where the student possesses sufficient information to proceed to the practical learning of AM. The second part from the assignments is presented in Figure 23.

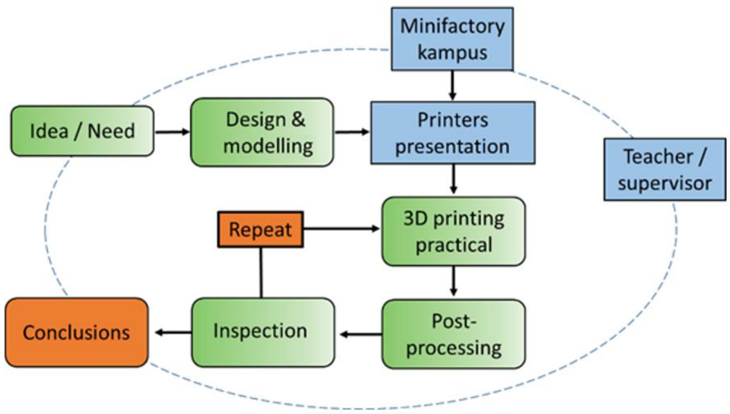


Figure 23. The second part of the learning assignments (Pikkarainen, Piili and Salminen, 2017).

As seen in Figure 23, the student is introduced to the practical side of AM through AM design work and proper introduction of the printers including the safety issues. The second part of the learning assignments introduces the student to the design, implement and operate phases of the CDIO process where the student deals with design work and implements the printing work through operating, analysing and investigating the outcome. This helps the students to master the deeper knowledge of technical issues and fundamentals (Crawley et al. 2014). The design work is based on the new AM-based PD model and general DfAM principles. When the students are introduced to the printers, they can proceed to the generic AM process repeating it as long as the result is successful. Diegel et al. (2019) stated that deeper learning of AM with all of its details requires these kinds of learning actions where the student designs a part and prints it by themselves. This view supports the creation of this kind of learning assignment. The printer manufacturer (Minifactory) had an online learning platform which helped the students in solving possible problems in the printing process, called Minifactory Kampus. The second part from the learning assignments was based on PBL, PjBL and CL, where the students reflected on the acquired knowledge from the first part of the learning assignments in a practical environment in groups dealing with issues and problems presented by the AM process and design work. This part was used as a background for further development of the learning methods as presented in P5.

## 4.2 Publication II

### 4.2.1 Objective

The purpose of the second publication was to investigate the pedagogical elements of AM and develop a model taking the pedagogical and technological perspectives of AM into account and to be used in AM education. The starting point for this study was the need for pedagogical development of AM regarding the gap in the current literature as presented in P2. The goal was to investigate the pedagogical and technical elements of AM and include these elements into the curriculum development forming the first part of the methodology of this thesis. Furthermore, one goal of this study was to research the learning process of AM and create an understanding of the learning of AM.

### 4.2.2 Results

Based on theoretical information from chapter 2.5. of this thesis, the more detailed implementation of AM education point of view concerning the knowledge transfer principle (U-I) led to the discovery of an improved knowledge transfer process as presented in Figure 24.

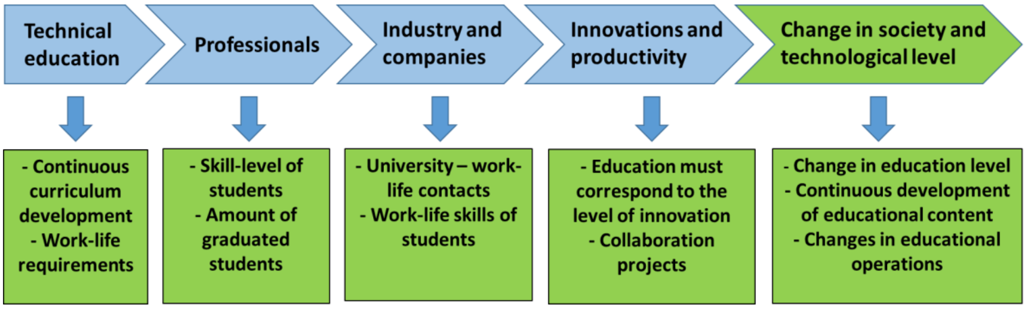


Figure 24. Improved knowledge transfer process (Pikkarainen and Piili, 2020).

As seen in Figure 24, the *improved knowledge transfer process* presents the distribution of AM knowledge from education (universities and universities of applied sciences) to companies ultimately leading to changes in societal and technological level as the innovation capacity and profitability improves. The process was created in order to emphasize the role of educational factors, such as curriculum, in the knowledge transfer. This discovery laid the theoretical foundation for this thesis concerning the connection of education and work-life. This improved knowledge transfer process presents what is required when arranging technical education based on work-life needs and it developed the literature findings further. This was seen as an important factor in the arrangement of AM education since the literature review presented the importance of work-life connection with AM education. The literature review pointed out the popularity and importance of AM in different educational areas, but a lack of description of the nature of AM learning in literature was noticed. This led to the description of *inversely proportional learning of AM* as presented in Figure 25.

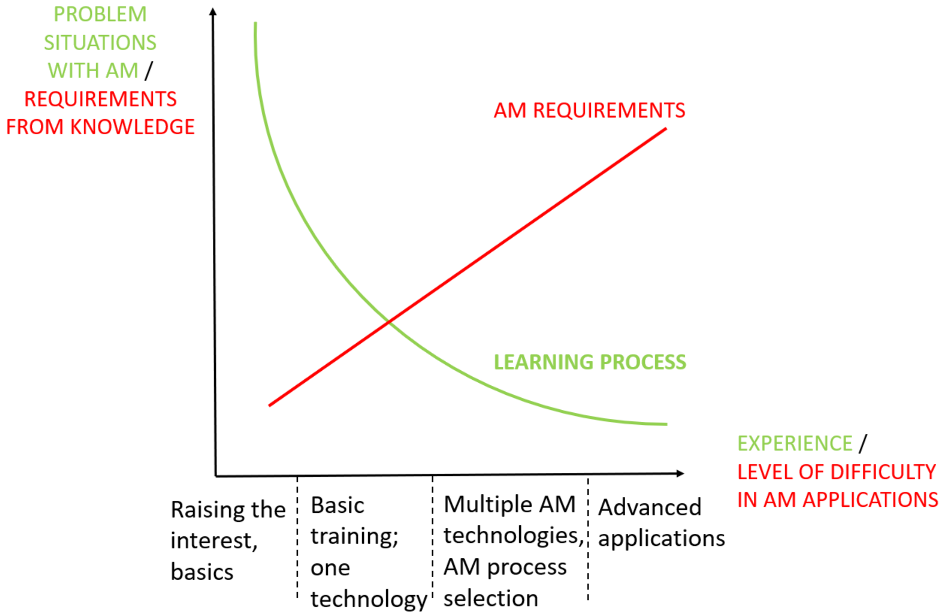


Figure 25. Inversely proportional learning of AM (Pikkarainen and Piili, 2020).

As seen in Figure 25, the description of inversely proportional learning of AM presents the typical process for learning AM in, e.g. universities and universities of applied sciences. The author´s experience from AM courses was connected to deductions from findings in the literature used to create this model. When approaching the nature of learning AM, there was no clear model to be found from the current literature. Rüütmann and Kipper (2016) indicated that learning in engineering requires measures beyond traditional pedagogics in order to train professionals. Karyotaki and Drigasm (2016) noted that the metacognitive process in problem-solving is an essential element when learning, e.g. technical skills. This refers to the student´s conception of his/her skills in problem solving from the perspective of amount of knowledge. These literature findings gave direction to the creation for a novel model which would describe the nature of learning of AM in a way which would take the learning process into account. The model takes the nature of the learning curve of AM into account where the learning is most challenging in the beginning due to the lack of knowledge and experience. Even though the requirements for AM technology is rather low at this point (usually material extrusion is the first technology to be used due to its simplicity and popularity and since it is the most used AM technology according to Gibson et al. (2021)), the student faces most of the problem situations at this phase. As the learning process progresses, the student gains experience and knowledge and is able to proceed to more advanced application in AM with other AM technologies. This was one important discovery from this study supporting the main research line of this dissertation, i.e. the research on learning multiple AM technologies. The learning becomes easier while the requirements from AM increase, hence the inversely proportional nature of the model. The model is divided into four phases presenting the structure of the AM learning process. In the beginning the interest towards AM is raised, proceeding to learning one AM technology (material extrusion). This leads to learning with multiple AM technologies and as the expertise of a student evolves, more advanced situations with AM can be dealt with. This enables the student to develop into an independent AM expert able to understand the possibilities and nature of AM deeper. This is the target level of AM education achievement required for educating engineers for AM-related work in companies.

The observations regarding the improved knowledge transfer process and the nature of learning of AM led to the *structure of curriculum with AM perspective* as presented in Figure 26. It was noticed that efficient AM knowledge transfer requires proper arrangement of AM education at the curriculum level. The need for AM-based curriculum was noticed also by Mehta and Bernadier, 2019; Alabi et al., 2019; Ford and Minshall, 2019 and Borgianni et al., 2019, which supported the results of P2 regarding the curriculum arrangement. The development of the arrangement was based on the Lapland UAS mechanical engineering curriculum, which is a knowledge-based curriculum concentrating on semester-centred projects together with supportive courses (Lapland UAS, 2015).

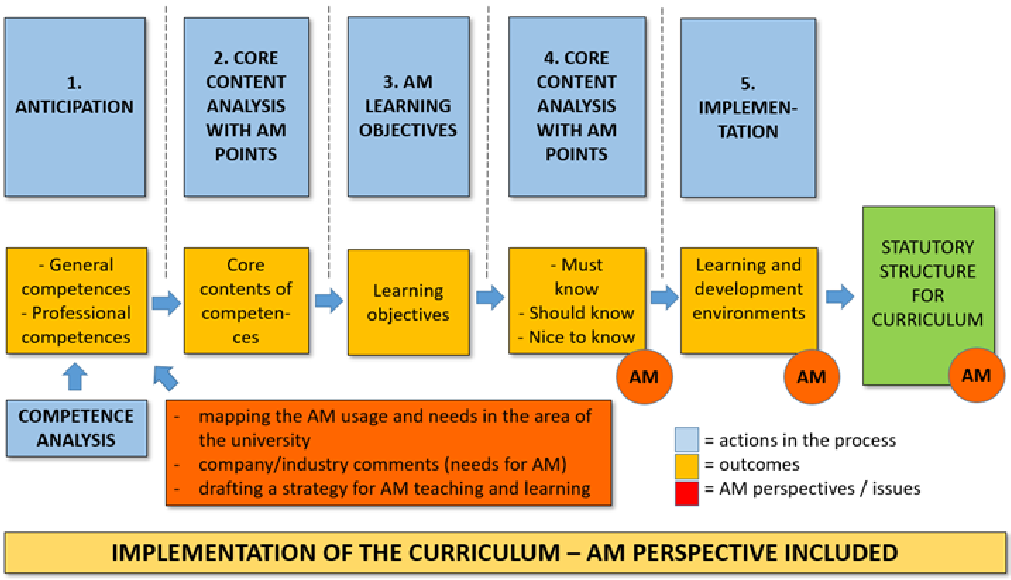


Figure 26. Curriculum with AM perspective (Pikkarainen and Piili, 2020).

In Figure 26, the blue boxes present the traditional curriculum process as actions to be taken. The orange boxes present the outcomes from these actions leading to the structure for the curriculum. The red areas present the AM perspective which is included in different action phases. This ensures the creation of AM-based learning outcomes and courses leading to the development of AM learning environments. This discovery supported the study as presented in P3 and P4 of this thesis.

It was noticed that curriculum is a tool for arranging the AM education but a more detailed description of the pedagogical element was needed in order to give a wider platform for the education. This was the origin for *the model of technical pedagogy* which gave the description for the AM pedagogy based on technical perspectives. The model for technical pedagogy is presented in Figure 27.

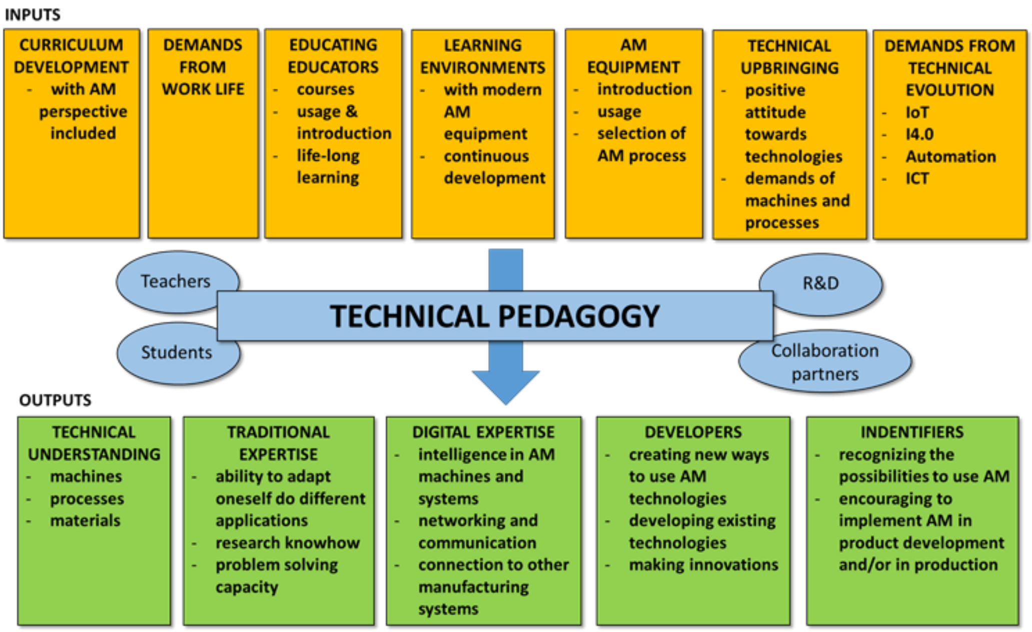


Figure 27. Model of technical pedagogy (Pikkarainen and Piili, 2020).

As seen in Figure 27, the model of technical pedagogy consists of inputs and outputs presenting the factors technical education needs to consider when arranging, in this case, AM education. The required inputs for AM education are based on the literature review and on the experience and observations of the main author of P2, the author of this thesis and educator of mechanical engineers. The inputs were identified as curriculum development, work-life demands, the education and know-how of the teachers, practical AM learning environment with proper and up-to-date AM equipment, technical upbringing of the students and last, the demands set by general technical evolution such as the Industry 4.0 elements. These inputs are then handled by the operators of the model, i.e. the teachers, students, R&D personnel and collaboration partners functioning in different areas of the model and AM education. Teachers and R&D personnel are the enablers and builders of the AM education and research substrate; students are the target group for the model. The role of collaboration partners can be as customers and in addition, a substrate for the used inputs of the model.

The outputs can be used as a checklist of factors required in the implementation of AM education. The outputs present the outcome from the learning of AM, i.e. technical understanding, traditional expertise and know-how, digital expertise, development abilities and last, the awareness to identify the possibilities to use AM in different areas. These outputs can be reflected when creating learning outcomes for AM education as presented in P4. The model implements the knowledge transfer principle presented in this study and it can be used by educators in the field of engineering. The model enables the use of desired technology (AM is used here as the origin) by reflecting and adjusting the inputs and outputs according to the technology. The model works as a checklist when implementing the education of technical subjects and gives an understanding of what is required when combining traditional pedagogics with technical subjects. In addition, it gives an understanding of the required factors when arranging practical education for a technical subject. The model helps in the curriculum development work by providing a tool for identifying desired learning outcomes and it presents all the users who function within the model. This model of *technical pedagogy* is the main result of P2 and one of the main outcomes of this thesis. Technical pedagogy provides a solution for keeping technical education up to speed with basic technological development and arranges the education according to work-life requirements.

## 4.3 Publication III

### 4.3.1 Objective

The aim and purpose of the third publication was to design a practical learning environment for AM. P3 forms the second part of the methodology of this thesis by presenting a study for creating a functional and occupationally safe 3D printing learning environment. The need for developing the practical side of AM education was the motivation for this study. The study combined design guidelines and the safety of AM through occupational safety and the functions taking place in the AM environment. The secondary objective was to develop a description for the operations taking place in the environment enabling the connection of AM to a manufacturing chain, for instance, and show a functional model for a 3D printing laboratory.

### 4.3.2 Results

The P3 literature review gave an overview of the safety of AM in different phases, which was the starting point for the design work. In addition, it provided the material for the *occupational safety of the learning environment* and collected the literature information from Unwin et al., (2013), Stockmann-Juvala et al., (2016) and the Finnish Institute of Occupational Health, (2016) into one figure to be used for educational purposes. The literature review presented the lack for practical safety solutions (e.g. casings for open-type printers). One motivation for the creation of guidelines for the occupational safety of AM was the AM learning environment development which could then be used as an example from an occupationally safe AM learning environment. Figure 28 presents the safety of AM.

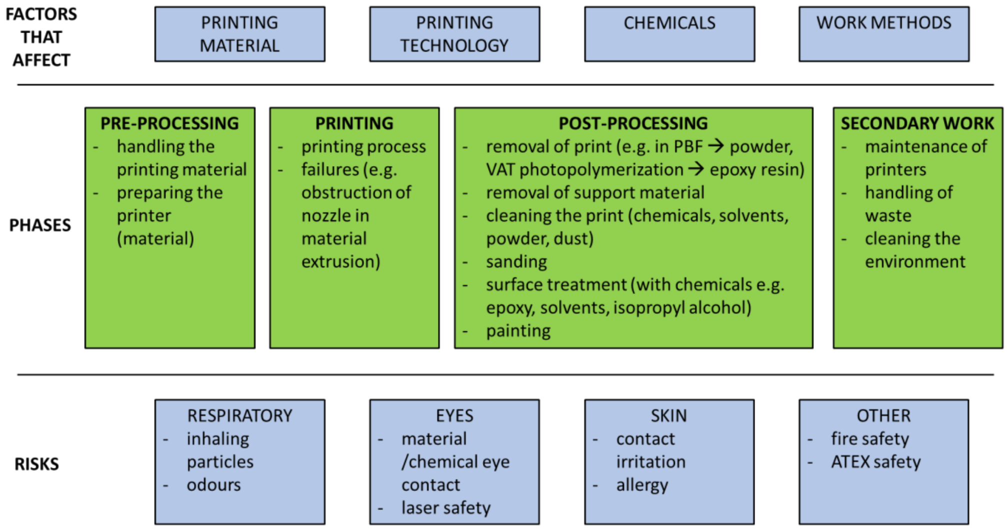


Figure 28. The factors affecting the safety of AM (Pikkarainen, Piili and Salminen, 2020).

As seen in Figure 28, the four main phases of the AM process, pre-processing, printing, post-processing and secondary work, contain several tasks including the possibility for hazard. Material, selected technology, chemicals (e.g. isopropanol alcohol, liquid resin) and work methods presented the factors affecting the generation of risk. The main risks were connected to respiratory, eye and skin contact and to other possible occasions where injury might happen. Alongside the AM laboratory design work, Figure 28 was used in the AM courses and was considered to be a very illustrative presentation from the safety of AM. This figure presented all the main issues concerning the safety of AM and was a very informative way to emphasize the safety factors to the students. This guided the study when the safety solutions for handling the emissions were designed. In addition, the literature review gave other guidelines such as how to work safely with the chemicals and handling waste, just to mention a few. One output from the literature review was the use of fully encased printing solutions to handle AM emissions, as presented by Zontek et al. (2016) and Viitanen et al. (2016). The implementation of printer safety was based on the literature review from particle emissions regarding 3D printing. The study resulted in the modular design of casings. This enabled the use of the same design with various open-type printers and enabled flexible working with the printers. The air extraction was implemented via an air extraction outlet from the top of the casing connected to the main air extraction duct of the new AM laboratory. The frame of the casing consists of aluminium profiles with embedded PC-sheets as walls. The casing has doors with magnetic locks. The air extraction causes negative pressure inside the casing causing the air flow from inside the casing to the outlet. The necessary supplementary air comes from the gaps in the structure ensuring the removal of micro and nanoparticles. The measurement of the air flow was not a part of this study as it will be implemented during the installation work of the casings in spring 2021.

The safety factors had to be connected to the operations taking place in the AM laboratory and regarding the operations, the main output from P3 was the *AM environment function model* as presented in Figure 29.

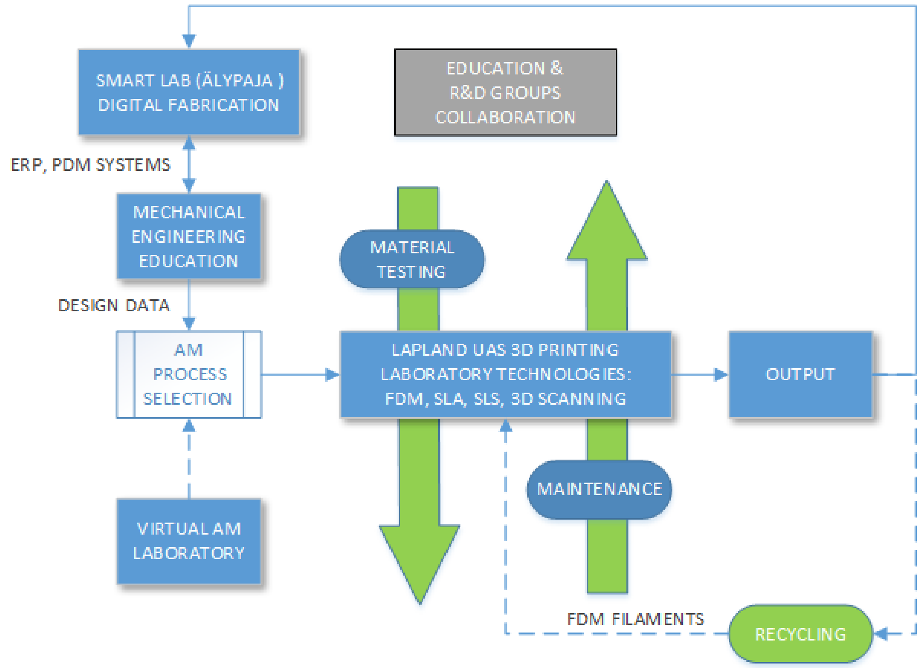


Figure 29. AM environment function model (Applied from Pikkarainen, Piili and Salminen, 2020).

Figure 29 presents the simplified version from the AM environment function model; the detailed version can be seen in P3. The function model presents how the AM environment can be connected to a product manufacturing chain, including design and manufacturing phases. In the centre of the model is the new AM laboratory. The outputs from the laboratory include, e.g. AM parts and products, student projects and prototyping services. In the background of the laboratory are the different R&D research areas such as material testing and maintenance integrating the R&D functions and groups into education. This collaboration brings valuable research knowledge to education as the Lapland UAS R&D functions are development projects connected to companies and industrial actors.

The model connects AM to the Smart Lab concept enabling a process where a product idea can be developed into a product. The Smart Lab was an EU-funded project, where digital manufacturing expertise and equipment was acquired. The Smart Lab is a digital manufacturing factory implementing the principles of modern manufacturing methods according to Industry 4.0 principles (automation, robotics, machine vision etc.). This presents the possibility to use AM in a product manufacturing chain alongside modern intelligent manufacturing methods. The Smart Lab was not part of this study although the AM learning environment is a part of this concept and the equipment of the AM laboratory was acquired with the project funding.

Mechanical engineering education presents the “engineering design office” and it includes the traditional engineering subjects such as product development and manufacturing methods which are one of the main areas of Lapland UAS mechanical engineering education. In addition, mechanical engineering education includes the engineering design process which is an essential part of product manufacturing. The Smart Lab is connected to the engineering design through ERP and PDM systems enabling a real-life digital system for product manufacturing. The output from this is the design data which is processed through the AM process selection model. The AM process selection model facilitates the selection of a suitable AM process for manufacturing and it is presented later in the results of P4. In addition, the model includes a virtual AM laboratory which can be used in training the students before actual laboratory exercises. The development of the virtual laboratory was not part of this study as it is included in the future development goals. The AM environment functional model can also be used in companies when the Smart Lab concept is replaced with the company´s manufacturing process while the engineering education is replaced with the company´s product development functions.

The last stage was to create a physical environment, where the operations would take place. Concerning the practical side of AM education, the main output from P3 was the *design for the new AM laboratory* including layout, electrical, air extraction, furniture and logistical operation design. The design for the new laboratory is presented in Figure 30.

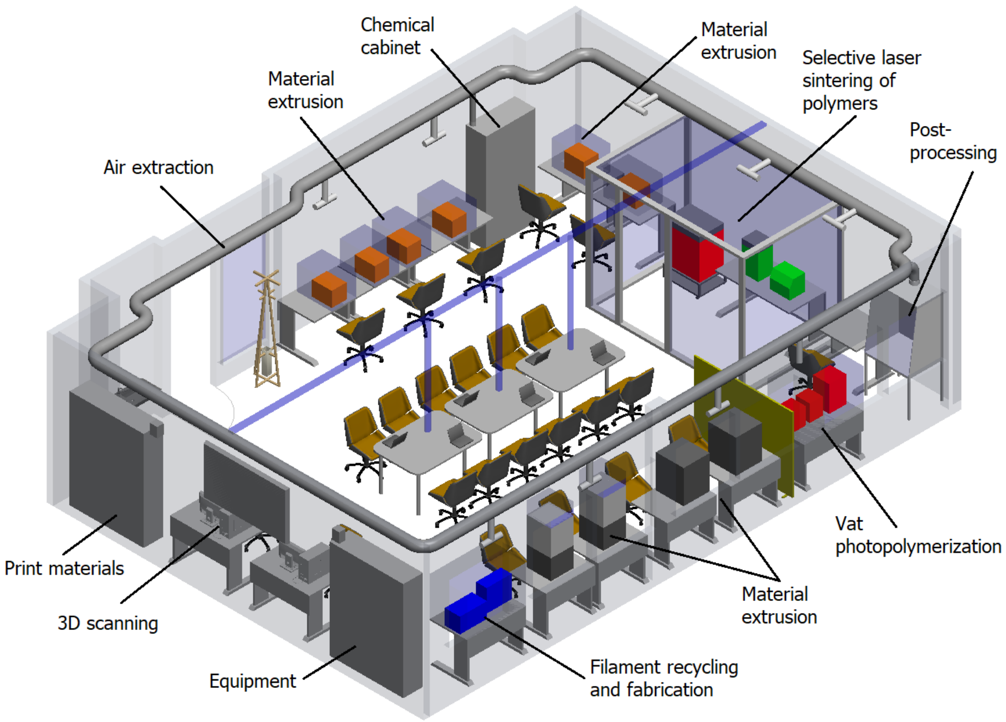


Figure 30. Design for the new AM laboratory (Pikkarainen, Piili and Salminen, 2020).

As seen in Figure 30, the layout presents the placement of the AM technologies. Each printer is connected to the main air extraction duct via casing and flexible PUR-hose (open-printers) or directly with flexible PUR-hose (closed printers). The environment includes 3D scanning and equipment for recycling parts (printed with material extrusion) and manufacturing new filament. The environment includes also areas for working and post processing and cabinets for chemicals, printing materials and other equipment such as tools. This design presented a case study which can be used in other similar development projects in universities and companies. The design work was based on the requirements from occupational safety regulations and presented a practical solution for how to arrange the safety with regard to the emissions of 3D printers.

## 4.4 Publication IV

### 4.4.1 Objective

The aim and purpose of this study was to map the requirements of work-life regarding the arrangement of AM education and to create novel learning outcomes based on the requirements. P4 forms the first part of the verification of the methodology of this thesis and it was based on the work-life point of view to AM education. The main motivation for this study was to connect the companies and industrial actors to the development of AM education. This derived from the need to increase the awareness about the possibilities to use AM in companies in the area of Northern Finland. The goal was to implement the AM topics in courses through curriculum work by creating novel learning outcomes for AM education. A secondary goal was to introduce a new AM process selection model which would facilitate the learning of AM in the beginning of the learning process.

### 4.4.2 Results

Table 2 presents an example from the analysis of the questionnaire responses based on Bloom´s taxonomy. The complete listing of the derived learning outcomes can be seen in Appendix D.

Table 2. Example from the responses and drafted learning outcomes (Pikkarainen, Piili and Salminen, 2021a).

| QUESTION TOPIC = COMPETENCE<br>Average > 8.0 | CATEGORY | LEARNING OUTCOME<br>(The student…) |
|---|---|---|
| 1. Basics of 3D printing<br>- AM technologies<br>- AM principles<br>- AM process | KNOWLEDGE<br>KNOWLEDGE<br>COMPREHENSION<br><br>EVALUATION | Can identify different AM technologies<br>Can define the AM principles<br>Is able to compare AM processes and distinguish them from each other<br>Can select the most suitable AM process for application |
| 2. 3D printing of metals<br>- technology, possibilities | KNOWLEDGE<br>COMPREHENSION | Can identify the possibilities of metal 3DP<br>Understands the basics of metal 3DP<br>Can differentiate metal 3DP from polymer 3DP |
| 3. Design principles (DfAM) | COMPREHENSION<br>APPLICATION | Understands the meaning of DfAM in design work<br>Can apply the DfAM principles in design work |
| 4. Optimization of 3D models (e.g. topology optimization, part consolidation) | COMPREHENSION<br>APPLICATION<br>ANALYSIS<br>SYNTHESIS | Understands the meaning of structural optimization in AM<br>Can perform str.opt. based on engineering design principles<br>Can distinguish the targets for optimization<br>Can design optimized structures for AM |

As seen in Table 2, the responses to questions 1-4 present answers with mean a value over 8.0. and the derived learning outcomes through the analysis. In addition, the questionnaire included the question *"What kinds of expertise does a future engineer need regarding the usage of 3D printing in companies and industry?", with* the responses given as free-form answers. Table 3 presents the free-form answers together with the derived learning outcomes.

Table 3. Free-form responses and the derived learning outcomes (Pikkarainen, Piili and Salminen, 2021a).

| QUESTION TOPIC = Free word | CATEGORY | LEARNING OUTCOME (The student...) |
|---|---|---|
| 12. 3D printing in engineering<br>- as a part of traditional mechanical engineering<br>- possibilities and limitations<br>- distinguish different applications<br>- reflecting into real situations (e.g into function principles of machines) | COMPREHENSION<br>COMPREHENSION<br>APPLICATION<br><br>ANALYSIS<br><br>ANALYSIS<br><br>SYNTHESIS<br><br>SYNTHESIS | Can illustrate mechanical functions through 3DP<br>Understands the possibilities and limitations of 3DP<br>Can identify the possibilities and limitations of 3DP in mechanical engineering<br>Can distinguish 3DP as a manufacturing method from the traditional ones<br>Can distinguish different 3DP applications (prototyping, small series, mass production)<br>Can combine 3DP into traditional mechanical engineering topics<br>Can adapt 3DP into real situations (e.g. mechanical functions) |
| 13. 3D printing and life-cycle<br>- spare parts and product life-cycle | COMPREHENSION<br>APPLICATION | Understands the role of 3DP in part life-cycle<br>Can identify the targets for spare part production through 3DP |
| 14. 3D scanning knowhow<br>- basic understanding and applications | COMPREHENSION<br><br>APPLICATION<br>SYNTHESIS | Understands the principle and possibilities of 3D scanning in 3DP<br>Can use 3D scanning in the production of data for 3DP<br>Can compile and covert 3D scan data into a format for 3DP |

As seen in Table 3, the free-form answers were combined into three competence areas presenting clearly the latter part of the Bloom´s taxonomy. The answers emphasized the importance of AM in engineering and the concept of product life-cycle. The derived learning outcomes were connected to the curriculum through a competence matrix. The matrix and explanation can be seen in Appendix E.

The second result was based on the research from the selection criteria of AM technologies. The goal was to create a model for the selection of the most suitable AM process, which would help students in the early phases of their AM learning path. Mançanares et al. (2015) presented a method for selecting AM processes based on part selection criteria including factors such as accuracy and surface quality. Liu et al. (2020) presented a decision-making methodology for selecting AM processes. Wang et al. (2017) presented a review from different AM selection process selection methods and selection attributes referring to the DfAM principle. These provided a background for the development of a novel and graphical AM process selection model which would take the education point of view into account together with the engineering design perspective. This was the main motivation for creating this model since the current literature did not provide one clear model for this purpose. Figure 31 presents the idea for the model.

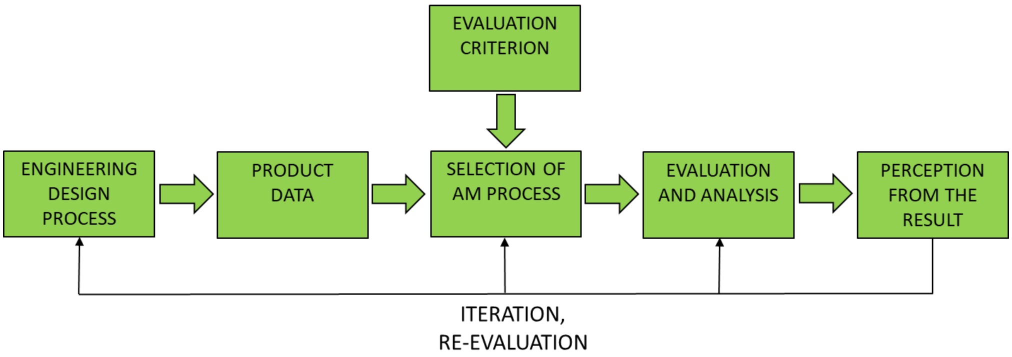


Figure 31. Preliminary process for selecting a suitable AM process (Applied from Pikkarainen, Piili and Salminen, 2021a).

As seen in Figure 31, the original idea for the AM selection process started from a traditional engineering design process which results in product data (including 3D CAD model). This data would then be analysed and compared with different selection criteria such as material, functionality, use-case, visual appearance, surface quality and accuracy, just to mention a few. The different AM processes in relation to the criteria would be evaluated and analysed leading to perception and the selection of the most suitable AM process. If the result from the AM manufacturing process would not be successful, the process would enable iteration and re-evaluation in order to improve the result. This preliminary model was used as a foundation for a more detailed AM process selection model. The developed *new AM process selection model* is presented in Figure 32.

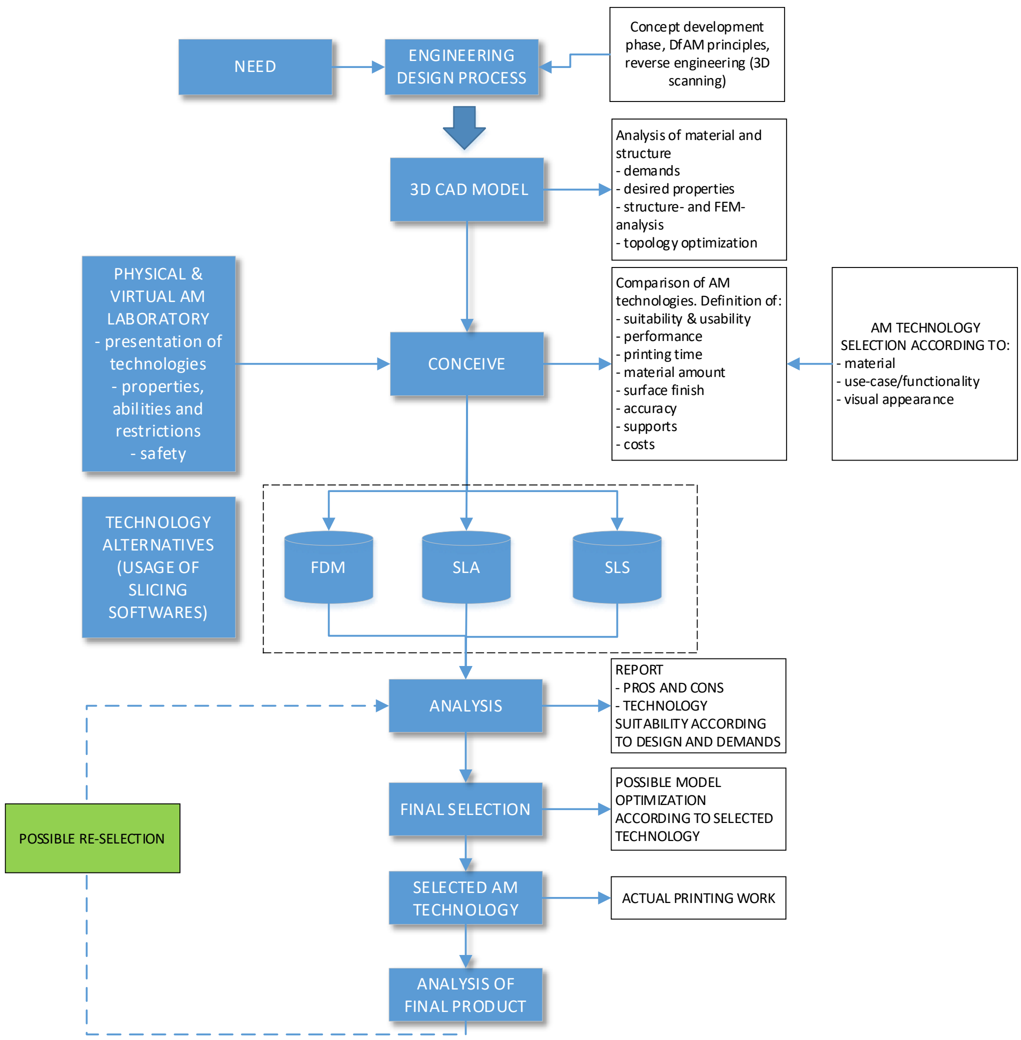


Figure 32. New AM process selection model (Pikkarainen, Piili and Salminen, 2021a).

As seen in Figure 32, the model starts from the basic engineering design process where the product concept is developed. The output is the 3D CAD model which can be analysed according to materials suitable for the process and required properties. In the conceive phase, the student is introduced to the AM laboratory in order to be able to work with the AM equipment. The required theoretical learning of AM precedes the use of this model in AM courses. In this stage, the student performs the comparison of AM technologies based on different selection criteria. In the next phase, the student is introduced to the required slicing software of available technologies. In this case, the technologies are material extrusion (FDM), vat photopolymerization (SLA) and powder bed fusion of polymers (SLS). The student analyses and reflects on the selection criteria for each AM technology reporting the pros‘ and cons‘ from each. The student can perform preliminary slicing work with the software in order to perceive the printing process better (e.g. the need for support material, layer height and printing time, etc.). Based on the analysis, the student makes the final selection and optimizes the 3D CAD model according to the selected AM technology, if necessary (e.g. the optimization of a part for vat photopolymerization; exit holes for excess resin from inside the part). The student proceeds to the actual printing work and by analysing the result, performs an iteration if necessary. The model is meant to support the student in the beginning of the AM learning path where the level of knowledge and experience from AM is lower. When the knowledge and experience increase, the selection will be more automatic and the process model can function more in the background of the selection work.

## 4.5 Publication V

### 4.5.1 Objective

The aim of P5 was to research mechanical engineering students´ perspectives on learning multiple AM technologies (FDM, SLA and SLS). The goal was to form an understanding of how the learning of multiple AM technologies progresses. P5 forms the second part of the verification of the methodology of this thesis through student perspectives. The study consisted of the AM technologies of the new AM laboratory and the investigation of learning concepts in order to form a view of how the learning can be identified. The investigation of the learning concepts and methods provided the background for a questionnaire which was completed by the students at the end of an advanced AM course.

### 4.5.2 Results

In order to map the perspectives and experiences of students learning multiple AM technologies, the question “*How do students learn AM?*” must be answered. The answer was found through literature review (theoretical basis) and the arranged AM course (practical basis). The literature review informed the study by identifying three different learning concepts, situated learning, practice-oriented learning and perceived learning. The goal was to reflect the learning methods and concepts, as presented in chapter 2.4 of this thesis, and form a combination where they would come together.  Figure 33 presents the *combination of the learning methods and concepts for AM.*

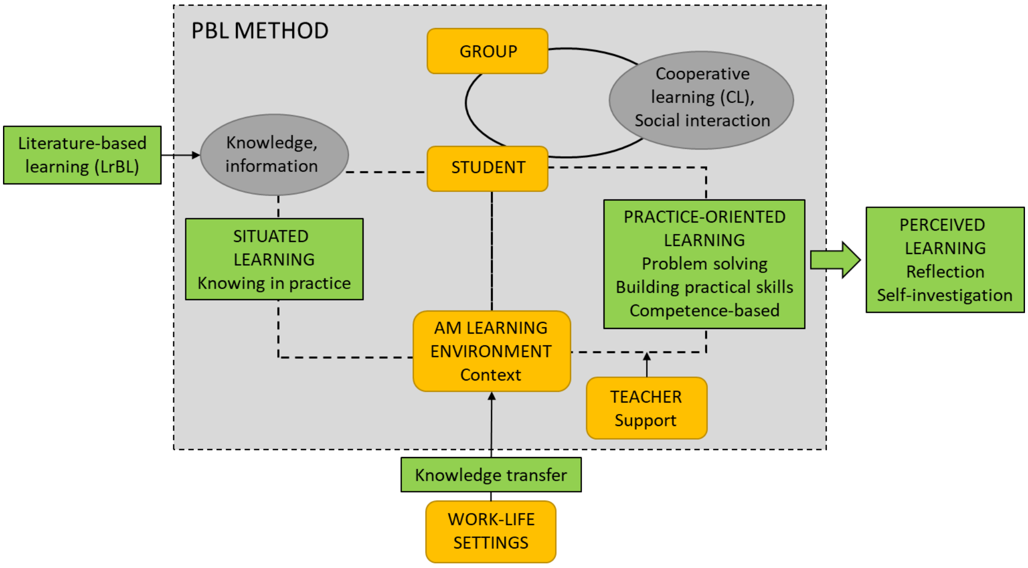


Figure 33. Combining the learning methods and concepts for AM (Applied from Pikkarainen, Piili and Salminen, 2021b; Askehave et al. 2015; Seidel and Schätz, 2019; Gary, 2016; Williams and Seepersad, 2012; Yang, 2019; Rüütmann, 2009).

As seen in Figure 33, PBL forms the background for the learning of AM. Depending on the work or project topic, the problem-solving process can be implemented through the PBL method. Through *situated learning*, the student can apply the acquired theoretical information from AM in an authentic AM learning environment (e.g. in AM laboratory). One good method for this is LrBL which enables sufficient theoretical knowledge required to function in the AM learning environment. LrBL can be situated outside the PBL process since most of the literature research will be done independently. The student uses the theoretical information through *practice-oriented learning* where the content of the learning is based on work-life. This can be, e.g. a project topic from work-life or learning certain AM technology according to the requirements of work-life. The teacher acts as a mentor and supports the learning process. In this context, the work-life setting is viewed as an outside factor in relation to the learning since the connection of education and work-life requires active interaction though communication or common projects; hence the importance of knowledge transfer. The AM learning is usually performed in groups which provides the possibility for CL and social interaction. As an output, the student evaluates his/her own learning through reflection and self-assessment leading to *perceived learning*. This is the one output of this thesis which studies the learning of multiple AM technologies.

The main outcome from P5 was the questionnaire completed by students regarding the use of multiple AM technologies simultaneously. The responses showed that students´ relatively high expectations for the course were met and that the knowledge and skill level improved during the course. This was positively indicated by the student responses, before and after the course. The introduction of FDM was seen as relatively easy indicating the preceding studies from FDM were effective. SLA technology was seen to be a bit more difficult to introduce while SLS was seen as the most difficult. The use of SLA and SLS software was seen as more difficult than that used with FDM. The responses regarding the design principles of the three technologies were considered equally easy. This showed also that the prior studies of the AM adaptation to design were useful. This helped the students progress into a more advanced situation concerning the DfAM principle in this course. As it was expected, the learning threshold of FDM was seen as the easiest, SLA was regarded as a bit more difficult whereas SLS was seen as the most difficult to learn. This indicated that SLS requires the most learning effort, which is an important observation for the arrangement of AM education. The AM process selection model was seen as relatively easy to use. The use of three AM technologies simultaneously did not presents major difficulties which indicates that the students are prepared to learn multiple technologies at the same time. The graphical presentations of the results of numerical questionnaire can be seen in Appendix F.

The responses regarding the use of multiple AM technologies simultaneously indicated that the most common answer was that the use of the technologies presents the possibility to compare the results from different perspectives. This indicates that the students are able to perceive the differences of the technologies better (e.g. material behaviour and accuracy, just to mention a few). The students felt that the use of multiple technologies strengthens the outcome of learning by providing a wider perspective to the technologies. Most of the students felt that their knowledge and skill level developed greatly during the course. In addition, the students responded that their motivation to use AM in manufacturing increased significantly during the course. The new AM process selection model was considered to be comprehensive and the students recognized the need to use the model in the beginning of the learning process of multiple AM technologies. Concerning the learning of each technology, the students felt that their expertise increased and their know-how became more versatile. The features and specifications of each technology were identified well. Concerning the difficulties of each technology, the students felt that FDM was already familiar and did not present any major difficulties. This supports the fact that FDM must be introduced before the usage of multiple technologies, as it provides excellent background for the learning of AM. The number of process phases in SLA was seen as challenging. The student had to memorize many work phases in the right order which was seen as a new issue to be dealt with. The design principles of SLA (e.g. support structure optimization) was seen as difficult since it plays a bigger part in SLA compared to FDM. SLS was seen as the most challenging, mostly due to the required amount of time the process takes together with the powder handling. The optimization of the print job and part orientation in the powder bed was seen as challenging, even though the software performs the nesting and orientation of the parts automatically. If the print volume was completely filled and optimized, it required more expertise due to the nature of heat distribution between layers. In the last part, the students were able to give free feedback on the course. The students wished there was more information and teaching related to the AM materials. In addition, the students realized the need for time planning, especially is SLS which indicated that the students´ capability for self-analysis developed during the course. The general feedback from the course was very positive as the students felt that they received a lot of new information from AM and appreciated the practical work with AM equipment.

## 4.6 Synopsis of the thesis and contribution to the whole

This thesis is based on publications P1-P5 and together with the results they form a research line where the learning methodology of AM is formed. Figure 34 presents the synopsis of the thesis and the interdependencies between the publications and results together with the contribution to the whole.

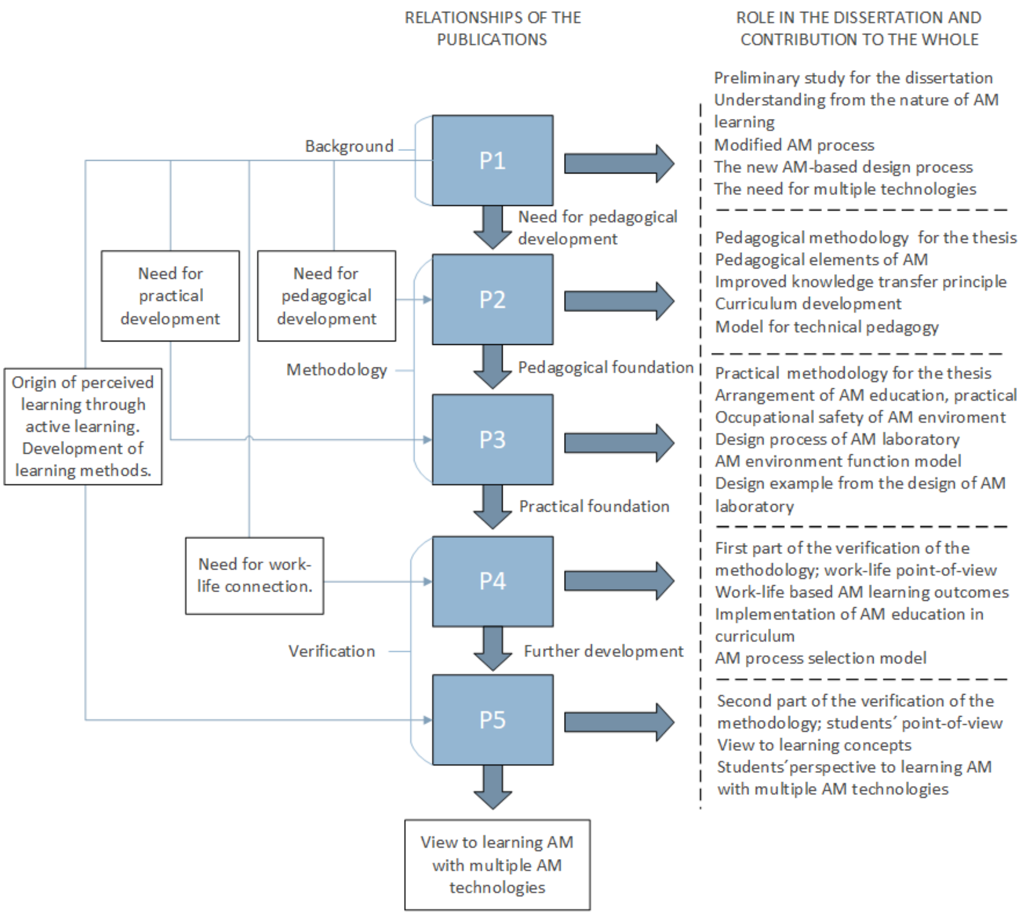


Figure 34. Synopsis of the thesis based on publications.

As seen in Figure 34, P1 is the starting point of the thesis by creating the research substrate for publications P2-P5 and providing the research background. P1 acts as a preliminary study for the dissertation by showing the need for pedagogical and practical development leading to the research presented in P2 and P3. P1 presented the importance of the work-life connection leading to the research presented in P4. The description of active learning, as presented in P1, worked as the origin for the research of learning concepts and methods leading to the research of perceived learning as presented in P5. The main output from P1 was the understanding from the nature of AM learning. It was noted that the implementation of AM into engineering requires the integration of engineering subjects, such as engineering design, with AM. Through this observation, P1 presented the new AM-based product design process. In addition, P1 presented the modified AM process which developed the generic AM process into a more detailed model. P1 suggested the need for developing AM learning through the use of multiple technologies which emphasizes the importance of P1 as the origin for this thesis.

The thesis continued with P2 as it formed the pedagogical methodology of the thesis by identifying the pedagogical elements of AM and the model for inversely proportional learning of AM. This was the continuation for the development of AM education. The experiences from P1 showed that the AM education requires a solid pedagogical background. Together with the literature findings, the author of this thesis realized that this requires an AM-based curriculum which was one of the main contributions of P2. These findings from the literature supported the need for integrating AM into the curriculum. In addition, P2 indicated the importance of curriculum planning in AM education. In order to create an AM-based curriculum, a novel model for technical pedagogy was created to understand the factors related to AM learning. P2 presented the improved knowledge transfer principle which presented the importance of AM education in technological development and competitiveness of companies. P2 formed the pedagogical foundation for P3 and P4.

In P3, the practical side of AM learning was researched through the creation of an occupationally safe AM learning environment. P3 formed the practical part of the methodology of this thesis. This study was connected to the development of the new AM laboratory where three different AM technologies, FDM, SLA and SLS were introduced. The literature review showed the lack of solutions for creating a physical AM laboratory and this was one of the main motivations for this study. P3 presented the required factors, such as practical and safety solutions, in order to create a functional AM laboratory. In order to understand the operation in the laboratory, P3 presented the AM environment function model. These were combined, as P3 presented a case example of how to design and implement a functional and occupationally safe AM laboratory. The results from P3 enabled the study presented in P4 by providing a practical foundation and environment where the AM education takes place.

P4 presented the arrangement of AM education by creating novel learning outcomes for AM learning based on the needs of work-life. The author of this thesis conducted this study in order to connect the companies and industrial actors to the development of AM education in order to strengthen AM knowledge transfer to work-life. The study presented the detailed implementation of the learning outcomes into the Lapland UAS mechanical engineering curriculum. Based on the need to use multiple AM technologies in learning (as indicated in P1), P4 presented the AM process selection model for facilitating the learning process. The study presented in P4 was the first part of the verification of the methodology presented in P2 and P3.

P5 continued the verification of the methodology by presenting the perspectives of mechanical engineering students regarding their learning of AM with multiple technologies. This study was meant to test the suitability of the learning factors (e.g. work-life based learning outcomes and the combination of learning methods and concepts as presented in Figure 33) presented in this thesis and form a view regarding how AM expertise develops during AM studies. This is an essential element when educating AM professionals according to the needs and requirements of work-life. The study presented in P5 was based on the study of perceived learning and it generated a model for the learning concepts of AM.

# 5 Discussion

The main objective of this thesis was to investigate the learning of AM and demonstrate that the learning of AM is more efficient when using multiple AM technologies simultaneously. The information received from this study is beneficial when transferring AM knowledge from higher education to companies. Based on the literature review performed in the publications and this thesis, it can be concluded that this cross-section of two areas, AM and education, has not been researched in the context of this thesis. The topic of scientific arrangement of AM education is relatively new and therefore this thesis brings novel research to this field of AM. The use of multiple AM technologies simultaneously was proved to be an efficient method to increase the skill-level and expertise of engineering students.

## 5.1 Answers to the research questions based on literature reviews

The main input for this thesis was the need for pedagogical development of AM education. This area of AM is relatively new and it has not been widely studied which presented challenges in the collection of theoretical data for this dissertation. The research questions were developed for guiding the study and their link to the publications can be seen in Table 4.

Table 4. Research questions and their connection to publications.

| Research questions | P1 | P2 | P3 | P4 | P5 |
|---|---|---|---|---|---|
| RQ1. How can traditional engineering education be combined with AM? | X | | | | |
| RQ2. What kind of pedagogical and practical solutions does AM education | | X | X | | |
| RQ3: How does the learning of AM work with multiple technologies? | | | | X | X |

As seen in Table 4, three research questions were developed in the beginning of the research to guide the synopsis of the thesis. Table 4 shows the connection between the research questions and publications which will be discussed in this chapter. One purpose of the publications was to perform literature reviews from different areas concerning the research overview of this thesis as presented in Figure 2. The performed literature reviews gave an outlook to the current status of AM education and to different pedagogical implications which could be applied in the learning of AM, especially with multiple technologies. The literature reviews presented a challenge due to the lack of pedagogical and practical solutions for AM education which would give a comprehensive outline guiding how the AM education should be arranged starting from the needs of work-life and ending at the pedagogical and practical arrangement of the learning. Therefore, the author of this thesis perceived the need to create a new pedagogical methodology for AM education for M.Sc. and B.Sc. levels of engineering. The following presents conclusions and answers to the research questions based on publications P1-P5 and the literature review of this thesis.

RQ1: How can traditional engineering education be combined with AM?

In this thesis, one important starting point was to view engineering design and AM as one entity, not as two separate branches of education. This derived from the experience of the author of this thesis which indicated that especially the design principles between traditional manufacturing methods and AM differ from each other and the students must be shown how they have to change their mindset. The professional literature of mechanical engineering is often straightforward and does not leave issues for interpretation. The literature from engineering design is more broad-minded, as it observes issues such as design choices which require intuition together with systematic thinking. AM presents a new kind of way of thinking, e.g. how the design choices should be made. This requires the identification of the differences and observations regarding how AM is different as a manufacturing method compared, e.g. to milling or turning. One important starting point for this is the traditional product design (PD) process as presented by Ulrich and Eppinger (2008) which has been one of the cornerstones of the Lapland UAS mechanical engineering education. The generic PD process model shows the stages of the PD process but does not take the AM design process into account. As indicated by Diegel et al. (2020) and Gibson et al. (2021), the AM manufacturing and design processes differ from the traditional manufacturing product design processes, such as milling and turning. The literature sources presented either single PD processes or AM design processes but not a model which would combine these two. Therefore, the author´s approach to the research question was to develop first an understanding related to the learning of AM. The author utilized his work as a senior lecturer from the area of mechanical engineering and developed the new AM design process model by combining the generic PD model and the AM process together, including the AM design principles and fundamentals for learning. This generates new ideas for the development of AM education (e.g. the usage of multiple technologies and the need for developing the AM laboratory). The model can be used to present how the AM product design process differs from traditional ones by taking, e.g. the DfAM principles into account when making design choices. One important phase is the selection of the AM process to be used, which gives the opportunity to introduce the new AM process selection model, as presented in P4. This is one indication of how engineering design can be combined with AM. The new AM-based design process contains many elements from the Ulrich and Eppinger (2008) model, but it updates the process to the era of AM. Findings from P1 gave a solid background for the implementation of AM in engineering education as it provides a new kind on product design process with AM perspective. RQ1 together with P1 formed the preliminary study for this thesis by providing a view to the elements of learning. P1 created the conceptual learning environment for AM education, which was seen as important when outlining the direction of this thesis.

RQ2: What kind of pedagogical and practical solutions does AM education require?

The findings from P2 and P3 presented the lack of pedagogical and practical solutions in the current literature concerning the arrangement of AM education and the methodology of this thesis. The performed literature reviews indicated that the literature consists of individual solutions (e.g. case examples where the results from an individual AM course are presented and analysed) but a comprehensive methodology was missing which could be utilized and adjusted to engineering education in general. This is one of the biggest obstacles in the wider adoption of AM into the manufacturing industry as presented, e.g. by Duchêne et al. (2016). This was also one of the main observations of the author of this thesis based on the experience from the field of AM education in Finland and Europe. One important outline for RQ2 was the need for knowledge transfer from education to work-life. The knowledge transfer methods for AM education were seen as the origin for the arrangement of pedagogical and practical methodology for AM in P2. Brans (2013) informed that the possibility of using AM as a manufacturing method boosted the popularity of the technology but Mebolt and Klahn (2017) presented the challenges associated with raising AM to the traditional manufacturing methods. These challenges were usually connected to technical issues and P2 suggests the conclusion that the intensification of AM education is the solution to the problems. Further, this thesis identified the challenges as being specifically related to the lack of pedagogical solutions for AM education. Tunca and Kanat (2019) and Shi et al. (2019) indicated that technical education is the starting point for knowledge transfer targeting changes in technological and societal levels. The theoretical material from U-I and I-U from the perspective of knowledge transfer is scattered and there was a need for the creation of a description for a mode of knowledge transfer that would be more comprehensive. Therefore, the author of this thesis created an improved knowledge transfer model and identified the necessary factors considering the arrangement of AM education. The improved knowledge transfer model, as seen in Figure 24, clearly supports the literature observation indicating the importance of technical education as a starting point for the transfer of AM expertise to companies. This is an important result since when adopting AM to, e.g. the manufacturing industry, the actors must be identified in order to start the necessary collaboration. Graduated engineers are one path for transferring the AM knowledge to companies but efficient knowledge transfer requires also active collaboration between higher education and work-life. Several results from this thesis, such as the work-life-based learning outcomes for AM education (as seen in P4) or the view of learning AM with multiple technologies (as seen in P5), are connected to the new knowledge transfer principle. This supports the view that by developing AM education, the AM knowledge transfer to companies becomes more efficient. Through this, the companies are able to use AM in their operations and improve profitability and competitiveness. This has a positive effect also on the economy and common technological development.

Curriculum development is an important solution from the pedagogical point of view in order to arrange proper AM education in this thesis. Lee et al. (2015) indicated that the connection between AM education and work-life requires AM-based curriculum. This was also noted by Seidel and Schätz (2019) and Ituarte et al. (2019). Assunçao et al.

(2019) also states that there is a need for AM-based curricula in Europe in order to educate qualified AM personnel. Popescu et el. (2019) summarized the AM-based curriculum aspects in higher education, presenting the importance of curriculum in AM education. The observations of the author of this thesis indicated that the traditional curriculum process offers only the tool for the solution, not a deeper pedagogical meaning. Therefore, it is important to research the nature of technical education further. The concept of technical pedagogy was created and could be used as a starting point for AM-based curriculum development. This kind of development is necessary in order to achieve a solid foundation for the implementation of AM to the curriculum. Curriculum is a tool for arranging education and it describes how the expertise of a student develops over the semesters. Therefore, the curriculum should be used to present the development of AM expertise of a student. The implementation of AM into a curriculum requires a new kind of perspective for the development work, hence the model of technical pedagogy. The model of technical pedagogy is a map for arranging technical education and it presents a novel way to view technical education, which is needed in order to modernize AM education. The practical implementation of the AM education happens through courses and projects presented in the curriculum. P4 presented the state of AM related courses in Lapland UAS mechanical engineering curriculum in a way which enables the development of expertise of students. The courses must be implemented within the curriculum in a way which forms overarching AM related learning path. When looking at the required number of courses, the minimum number should be at least three where the first introduces the basic principles and technologies of AM, the second would consist mainly practical work with the AM equipment and the third would function as advance study deepening the knowledge. This way the students can separate different areas better making the learning more efficient. This can be kept only as a suggestion as the real required number of courses depends e.g. on the requirements of work-life and the nature of the degree (whether it is concentrated to product development or manufacturing methods or not). The amount of ECTS credits, as presented in P4, can vary according to the learning path of a student. There should be sufficient amount of credits available from AM topics for the students to be able to choose from. This enables individual learning paths.

Detailed course plans contain all the necessary information for the actual implementation of learning (e.g. number of lectures and laboratory work, expected learning outcomes, contents and topics). Firstly, the learning concept(s) (situated learning, practice-oriented learning and perceived learning) must be selected to manifest the nature of learning in a course. Second, suitable learning method (PBL, PjBL, LrBL, CL) must be selected and planned according to the topics and time resources. The amount of guided/laboratory/independent work must reflect to the selected method and therefore require detailed planning. These pedagogical solutions form an important part of the AM learning methodology presented in this thesis. When viewing the implementation of the methodology in higher education (B.Sc. and M.Sc. levels of engineering), it can be noted that this methodology can be applied mainly in universities of applied sciences since the foundation of the methodology comes from work-life. The work-life perspective comes from the study presented in P4. The application of the methodology in universities would require more research, especially at the curriculum level since the results of this thesis are based on the UAS curriculum structure. The academic nature of the methodology could be suitable for universities, but the practical implementation would require more work. It can be noted that this methodology could be used as a starting point for developing AM education also in universities but requires more research for wider implementation due to the differences in the degree structures and level of academic nature.

The use of FDM, SLA and SLS were seen as a good starting point for the arrangement of AM education due to the relative ease of use and lower price compared to metal AM as indicated by Diegel et al. (2020) and Gibson et al. (2021). This was one of the starting points for the development of the new AM laboratory, which was at the centre of the study presented in P3-P5. In the beginning of the design work it was clear that one limitation for selecting the technologies was also the allowed budget and second, the higher demands of metal AM concerning the learning point of view. It was important that the selected technologies would allow the independent work of students, especially in the beginning of their learning path, hence the selection of FDM, SLA and SLS. The design process of the new AM laboratory, together with the AM-based curriculum development, gives a solid structure for AM education which can be used in other universities of applied sciences in their development work with such environments. If the AM education is arranged with the “technology-first” principle, without proper pedagogical planning, the learning is unorganized and complicates the principle of knowledge transfer.

P3 presented the kinds of practical solutions the arrangement of AM education requires. One important starting point was occupational safety (such as handling the particle emissions) presented by Viitanen et al. (2016), which suggested that the most efficient solution for handling particle emissions is to have fully encased printers. The literature review of P3 showed that there is a lack of technical solutions for the casing design and implementation. The author of this thesis has seen this issue also in AM laboratories in Finland and Europe and decided to make safety the most important starting point for the development of the new AM laboratory. Therefore, the students designed a preliminary structure for the casing which the author developed further in this thesis, as presented in P3. The design process of the new AM laboratory, performed by the author of this thesis, included the air extraction design for the casings leading to an occupationally safe AM environment. These safety measures addressed both chemical and work safety issues. The author noticed that when the students work in a safe environment where occupational safety is emphasized, the students´ positive attitudes towards safety develop. This enables them to take safety into account better, also in other situations such as internships. The field of mechanical engineering usually involves hazardous work, such as in paper and steel factories. Gharibi et al. (2016) presented that the workers´ attitudes towards safety are linked to accidents. If the workers are more aware and educated on safety issues, the risk for accidents decreases. In addition, Terziev et al. (2020) indicated that occupational safety is an important factor in productivity and profitability. The literature findings support the new knowledge transfer model, as presented in this thesis, where education is the starting point for transferring knowledge to work-life.

During the design process of the AM laboratory, it was noted that the practical solutions for the AM environment must be included in the design for the environment´s functionality. Therefore, the author created an AM laboratory function model connecting AM to a manufacturing chain. The educational point of view was included in the form of engineering design. The model expands the perception from the use of AM as a part of a manufacturing process, as it includes the perspective of AM process selection and applications, research and education. This was an important observation and output since the adoption of AM requires its integration into other functions. AM is often dealt with as an individual method or process, especially in education, and the wider adoption of AM into the manufacturing industry and education requires proof that AM can be a part of a manufacturing chain. The findings from this thesis regarding the AM laboratory function model is an example of this. Therefore, the importance of the AM laboratory function model is significant in the field of AM education.

RQ3: How does the learning of AM work with multiple technologies?

Drafting the answer to RQ3 required the verification of the methodology as presented in Figure 3. As presented in P2, one key element for arranging AM education is the implementation of AM into the engineering curriculum. P4 addressed this issue by developing novel learning outcomes based on the needs of work-life. As presented by Lloyd´s Register Foundation (2016), the path to a competent and skilled workforce starts from an academic framework regarding the use of AM in the manufacturing industry. This indicates the importance of AM education and especially the work-life connection in education. Assunçao et al. (2019) presented that the current AM education in Europe has problems keeping up with the speed of technological development. The observations of the author of this thesis indicated that this is a geographical issue. This is true in areas where AM is used widely in the manufacturing industry but, e.g. in Northern Finland, the wide adoption of AM in companies is still in the beginning stages; thus, the situation is opposite in these cases. The universities and universities of applied sciences are trailblazers in the development of AM knowledge and technology and it is their job to spread the information related to the possibilities of AM to companies and industrial actors, especially in areas where AM is not yet widely known. Engineering education requires close collaboration with work-life representatives in order to develop the quality of the education and therefore the concepts of knowledge transfer: I-U and U-I collaboration are important.

The observation of the importance of I-U and U-I collaboration was one important starting point for the research as the author conducted the questionnaire for work-life regarding requirements for AM education on the university of applied sciences level. The responses gave valuable information for creating novel learning outcomes for AM education and their implementation to the curriculum. This is an important step when implementing the knowledge transfer principle; the AM education must match the requirements of work-life. If the methodology would be applied to universities, it would require a more targeted questionnaire from the university perspective considering the more academic and research-centred nature of that level of education. By using Bloom´s taxonomy (1956) with the learning outcomes, AM was implemented into the curriculum. This enabled curriculum and course planning in a way which supports the development of a student into an AM expert. The author noticed that the implementation of AM into the curriculum was not enough since it did not address the pedagogical perspective of AM learning (e.g. how do the students learn AM, what is the most efficient way to learn AM?). Therefore, the author decided to investigate suitable learning concepts and methods in P5 in order to receive an answer to the questions regarding AM learning. The concept of perceived learning, as presented in Bacon (2016), Zhang (2016), Suhoyo et al. (2017) and Möller and Shoshan (2019), described the nature of AM learning well, but the author decided to investigate the nature of this further in order to identify the learning factors in detail. The author combined perceived learning with the concepts of situated learning and practice-oriented learning, as presented in Besar (2018), Handley et al. (2007), Smirnova et al. (2019), Chuchalin and Vyuzhanina (2014), Whelan et al. (2016) and Abykanova et al. (2017). This combination model, as presented in P5, described well the nature of AM learning and a decision was made to use it as a foundation in the research regarding the learning of AM. The author used this combination in a wider context in this thesis when the theoretical foundation of this thesis was constructed. This led to the model, as presented in Figure 33, combining the learning concepts of situated learning, practice-oriented learning and perceived learning into PBL, PjBL, LrBL and CL. This combination forms a view to AM learning which brings a novel contribution to the current research of AM education.

As proposed in P1, the development of AM education requires multiple AM technologies, which was one of the origins for P5, and the use of multiple AM technologies in AM learning. The introduction of multiple AM technologies presented a challenge for the students: how it is possible to select the most suitable AM technology for an application? Liu et al. (2020) presented that AM process selection is based on many special characteristics and it is connected usually to the end of the product design process. The study in P4 presented the need for the development of methodology for the selection of a suitable AM process from educational and technical points of view. P4 addressed this issue by developing a new AM process selection model helping students in selecting the most suitable AM technology for application. The author realized the need for this model when the decision to acquire multiple AM technologies for the new AM laboratory was made. Based on the literature review performed in P4, the author of this thesis created this model to be used in AM courses enabling the connection of engineering design processes to the AM process selection which was the continuation of the study presented in P1. The AM selection criteria, as presented by 3D Hubs (2019) and Gibson et al. (2021), were not sufficient as they only addressed the factors such as accuracy and visual appearance compared between different technologies. The author decided to create a model which would support the study presented in P1 concerning the AM product design process. This model works as a map for the students when they are designing parts and considering suitable AM processes for manufacturing. The functionality of the model was verified to be suitable for educational purposes based on the student feedback as presented in P5. Since the model is meant to raise student awareness of process selection, and it only presents the selected criteria for the process selection it was deemed as not sufficiently inclusive and therefore of less value. No single model is fully comprehensive and this model is one example of how AM process selection can be done in engineering education. The future use of the model will definitely present some development needs but it functions well as a starting point for the selection as it is.

The use of multiple AM technologies simultaneously in AM learning was not investigated in the current literature in a way which would have given answers to RQ3. Therefore, the author decided to use multiple AM technologies in an AM course and conduct a student questionnaire in order to generate an overview of student perspectives. The results showed that the use of multiple AM technologies simultaneously enhances the students´ know-how and skills related to AM. In addition, this strengthens the students´ development into AM experts since the learning is based on the needs of work-life, hence the learning outcomes are derived from work-life requirements.

## 5.2 Further outcomes

One of the main purposes of this thesis was to develop a methodology for AM education which would eventually lead to the wider adoption of AM into companies through improved knowledge transfer. The answers to RQ1-RQ3 led to the main outcome of this thesis as presented in Figure 35.

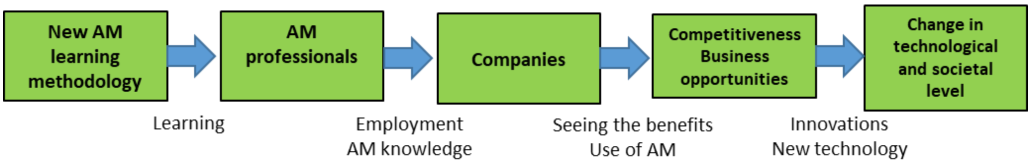


Figure 35. Main outcome of the thesis.

As seen in Figure 35, this thesis shows that the use of multiple AM technologies and the development of new AM learning methodology leads to the education of AM experts who are more aware of the deeper AM knowledge and able to perceive the possibilities to use AM as a manufacturing method. The methodology consists of the pedagogical solutions and practical solutions as presented in this thesis. As the students are employed in companies, the companies can see the possibilities and benefits of using AM in their manufacturing process. This leads to new business opportunities enabling better competitiveness. This can generate new innovations and technologies in companies as the companies develop their operations regarding AM. This leads to changes at technological and societal levels as the use of AM generates new research data and technological innovations.

This thesis suggests that the combination of AM and education has not been widely researched based on the literature reviews in P1-P5. The need for pedagogical development shows that the efficient arrangement of AM education requires a novel cross-sectional research area. The principle for the new research area is presented in Figure 36.

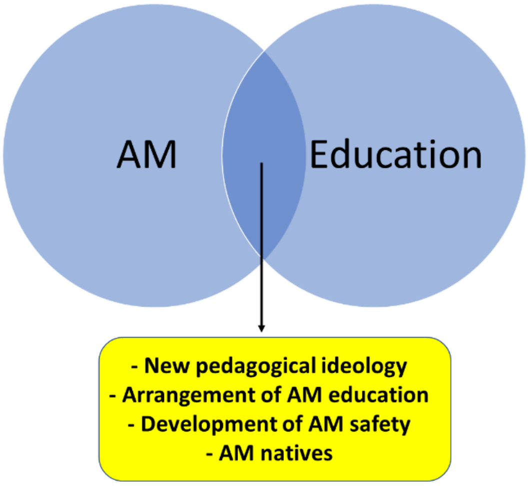


Figure 36. New area for research.

As seen in Figure 36, the cross-sectional area of AM and education generates a new area for research where traditional pedagogics are connected with new technological innovations. This produces new pedagogical ideologies where the traditional perspective to learning and teaching is updated. This enables the arrangement of AM education in a way which supports the technological evolution of AM. One important issue is the safety of AM (especially the attitudes towards it) and new pedagogical methods, based on technical perspectives, which improve the adoption of safety measures more efficiently. Last, this new area of research produces pedagogical data and experience enabling the creation of experts who can be called “AM natives” as they consider AM to be one of the traditional manufacturing methods. This will boost the AM development even further.

Concerning the implementation of the learning methodology of AM, more detailed table of course arrangement with pedagogical elements can be created based on the Lapland UAS mechanical engineering AM topics and courses as presented in P4. Table 5 presents the courses and an example, how the concepts and methods can be situated within the courses with relation to the growth of student expertise.

Table 5. Lapland UAS AM courses and pedagogical methods.

| Semester | Course | Learning concept | Learning method | Max. ECTS |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | Project: Product development<br>3D printing (book exam) | Situated learning | PjBL, CL<br>LrBL | 1<br>5 |
| 4 | Project: Prototype<br>3D Design of a product | Practice-oriented learning | PjBL, CL | 2<br>2,5 |
| 5 | Work-life project | Situated learning | PBL, CL | 5 |
| 6 | Project: Finding solution<br>3D Printing and applications | Perceived learning | PBL, CL<br>PjBL, LrBL | 5<br>5 |
| 7 | Project: Innovation<br>Future technology | Perceived learning | LrBL<br>PjBL | 5<br>2 |
| 8 | Bachelor thesis | Perceived learning | Selected combination | 15 |
| | | | **Max. Total** | **47,5** |

AM knowledge and experience increases

As seen in Table 5, the courses presented in P4 are connected to the learning concepts and methods, as presented in chapter 2.4. Table 5 presents the maximum number of ECTS credits available from AM topics. The final number of ECTS credits is dependent from the courses the students selects as an elective study or from topics within a course or project (e.g. in semester project or B.Sc. thesis topic). In addition, table 5 shows that in the beginning of the learning path, the learning concept is either situated or perceived learning enabling the learning process and the application of theoretical information in practical circumstances. As the student gains sufficient amount of information, he/she can reflect that information more efficiently enabling perceived learning, which is usually used in latter semesters. PBL method is usually connected to situated or practice-oriented learning, as presented in P5. PjBL is usually connected to learning happening in projects but it can be connected with PBL since they are not exclusive methods. LrBL and CL can be as supporting methods to PBL and PjBL and therefore, they are usually connected to these in courses. In addition to these courses, the student can select a LrBL-based book exam (5 ECTS) as a free-elective course from AM topics in semester 3 or 4 aiming to strengthen the theoretical information. Table 5 can function as an example from the implementation of pedagogical methodology in a course level which can help other educational practitioners in their work.

# 6 Conclusions

In this thesis, the learning of multiple AM technologies has been studied. Based on the publications and the results of this thesis, it can be concluded that by using multiple AM technologies simultaneously, learning becomes more versatile and efficient. This supports the development of a student into an AM expert. After graduation, the students export the AM knowledge to companies enabling them to benefit from the expertise of graduated engineers. The main findings from this thesis are divided into two main sections based on the nature of the findings.

## 6.1 Contribution to theory

This thesis contributes new theoretical discussion concerning the pedagogical arrangement of AM education. This thesis responds to the research gap related to the theoretical knowledge concerning the arrangement of AM education, which is scattered and unorganized in the current literature, as presented in P2 and P4. The contribution to the theory aims to present pedagogical methods for the arrangement of AM education. The contribution to theory can be divided into the following contributions.

*Improved knowledge transfer process.* The new process updates the general theoretical view of knowledge transfer emphasizing the importance of AM education. It presents the distribution of AM knowledge generated in universities and universities of applied sciences in order to enhance the competitiveness and productivity of companies. This is based on the concept of university-industry (U-I) knowledge transfer. This leads to new innovations and changes in technological and societal levels. The process presents the factors required to implement the stages of the new model and facilitate the development of collaboration between the educational sector and companies.

*Pedagogical foundation for AM learning*. This contribution connects the learning methods (PBL, PjBL, LrBL, CL) to the learning concepts (situated learning, practice-oriented learning, perceived learning) and presents the importance of perceived learning in AM education in problem-based learning of AM. In addition, this contribution presents a novel concept for a new type of model of technical pedagogy. The model helps to understand all the necessary technological factors when arranging AM education. It shows that traditional pedagogics can include detailed technical themes, not just the traditional academic disciplines such as knowledge and skills in general. The model generates novel perspectives to engineering pedagogics and it can be used in other universities and universities of applied sciences when arranging AM education.

*Curriculum arrangement for AM education*. This contribution presents the foundation for AM education through curriculum arrangement. First, a structure for the curriculum is created in order to present the necessary phases where AM must be applied. Second, the creation of work-life-based learning outcomes is important for the implementation of the new knowledge transfer principle. The new learning outcomes ensure the quality of AM education when they are based on real requirements from work-life. The arrangement of AM education requires the implementation of curriculum at the course level and this contribution presents the development of AM expertise during engineering studies by using the categorisation of AM learning outcomes. This generates the view of how the development of AM expertise during studies can be implemented.

*Perspective to the learning of multiple AM technologies*. The verification of the developed methodology for AM learning is important and this contribution presents the reflections of mechanical engineering students to the use of multiple AM technologies. This includes the identification of the inversely proportional nature of AM learning. This contribution is one of the main outputs of this thesis as it proves how the use of multiple AM technologies makes the learning of AM more effective. This has a positive effect on the development of a student into an AM expert who is able to export AM knowledge to companies.

## 6.2 Practical contributions

This thesis presents practical solutions which can be used in AM education in engineering education. The contribution to the practical arrangement of AM education can be divided into the following contributions.

*Modified AM process*. The modified AM process was developed to present the modified AM process model in order to facilitate the learning of students when using certain AM technologies. The process presents details needed in different phases of the AM process and it shows the possibility for iteration if some phases present failure. This process can be used in the learning of AM as it presents more information than the generic AM process.

*New AM-based design process.* The connection of engineering design and AM was one of the starting points for this thesis. It was noted that the traditional product design process was not sufficient for AM purposes. Therefore, the new AM design process was created in order to facilitate the AM-related design work. This process can be used in engineering education when AM is used as the manufacturing method. In addition, the process helps to understand the differences in design work between traditional manufacturing methods and AM.

*Description of learning assignments*. The practical arrangement of AM education requires the description of learning assignments. This contribution presents a two-phased learning process where the student must acquire the necessary theoretical background in order to be able to proceed to practical work with AM equipment. These learning assignments manifest the combination of learning concepts (situated learning, practice-oriented learning and perceived learning) and the combination of learning methods (PBL, PjBL, LrBL and CL) as a case example. This contribution can be used when implementing AM education.

*Design of an occupationally safe and functional AM laboratory*. This contribution presents a case example from the design of a functional and occupationally safe AM learning environment. This presents the factors affecting the safety of AM by connecting risks to the phases of AM work (pre-processing, printing, post-processing and secondary work). In addition, this contribution shows how AM can be viewed not only as an individual manufacturing technology, but as a part of a manufacturing chain. This is based on the concept of “from idea to a product” presenting how to use AM, e.g. in company functions.

*AM process selection model*. The use of multiple AM technologies requires analysis of the features of each technology when selecting the most suitable AM technology for application. The AM process selection model presents a solution where the engineering design principles are connected to the AM selection criteria and through conceiving and analysis, the most suitable AM technology can be selected. The model is meant to be used in the early phase of learning multiple AM technologies simultaneously. The model facilitates the learning in the beginning and as the expertise of a student increases, the student can perform the selection work without the process model. In addition, the model works as a check-list when selecting the AM technology.

*The development of Lapland UAS mechanical engineering AM education and laboratory*. This thesis was done alongside the development of the new Lapland UAS mechanical engineering AM laboratory. The arrangement of the AM education required research and this thesis provided necessary means to implement the development of the AM education, all the way to the curriculum level. The literature review in P1-P5 enabled the theoretical base for the development and the practical side of the methodology of this thesis provided the detailed implementation of the AM education (e.g. design process of the laboratory, novel learning outcomes).

## 6.3 Suggestions for future research

The topic of this thesis is relatively new since the research concerning the arrangement of AM education from pedagogical and practical points of view has not been widely studied in the current literature. This thesis presents many novel pedagogical and practical solutions for AM education and it works at the crossroads of traditional pedagogics and technology. This generates a new branch of academic research. The following presents suggestions for future research.

*Development of the practical learning of AM*. The learning assignments, as presented in P1 and P5, presented examples of how to implement AM education. The collection of student feedback after every course is vital in order to develop the assignments further. The perspectives on the use of multiple AM technologies, as presented in P5, presented also development opportunities such as detailed time planning when working with the printers. The use of multiple printers with student groups require concentrated solution for the booking of printing time in order to make the functions in the AM laboratory more fluent. In addition, the use of multiple AM technologies presents a variety of materials that need to be studied. This development of AM material education is an important supportive element to the learning of multiple AM technologies.

*Development of the AM laboratory environment.* Regarding the fast pace of the development of AM technologies, continuous development of the AM environment is required. The used technology becomes obsolete after a certain amount of time as new printers with more sophisticated features become available. Therefore, it is vital to follow-up the general development of AM technology in order to update the AM equipment in the laboratory when necessary. In addition, the development requires the follow-up of the use of AM in companies and matching the used AM technology to this.

*Development of AM-based research in the laboratory environment*. AM offers many interesting areas for research such as new applications, materials and design considerations. Therefore, the research activities should be intensified and connect functions in the laboratory to research work. This enable the student participation in to the research and enhances the students´ development into an AM expert. When the research work is connected, e.g., to real-life projects coming from work-life, the students can work at the interface between education and work-life.

*Intensification of work-life connection*. The know-how-based learning requires active connection with work-life as the students are studying AM subjects based on the requirements from work-life. Further questionnaires could be arranged in order to introduce the new AM learning environment to companies and map the possibilities for cooperation and common research projects.

*Application of the methodology at the university level.* This thesis is based on the AM education at a university of applied sciences level of engineering (B.Sc.). Some parts of the developed methodology could be applied directly at universities (M.Sc. level) but more detailed implementation would require, e.g., additional questionnaires for work-life and academic partners and research institutions.

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# Appendix A: Categorization of AM processes

**Material extrusion** uses polymer filament material which is fed to a heating chamber through feeding rolls. Material is melted in the chamber and the feeding rolls create pressure inside the chamber forcing the molten material through a nozzle of a certain diameter (this unit is called the printing head). Diameter of the molten material is constant and it is moved in order to form the desired pattern to a building platform which is heated in order to achieve necessary adhesion between the part and platform. The nozzle plays an important role in the process as it affects the form of the molten material in relation to printing speed and feeding speed of the filament. There are different ways for the movement to produce the print. The most usual way is that the printing head travels in xy-direction while the build platform moves in z-direction, the movement equals always one layer height. The principle is the same as in the other AM technologies; the new layer is printed on top the previous one. The adhesion between the layers is essential and they have to bond together in order to achieve the desired structure of the part (EN-ISO ASTM52900, 2017; Gibson et al., 2021; Kumar, 2020).

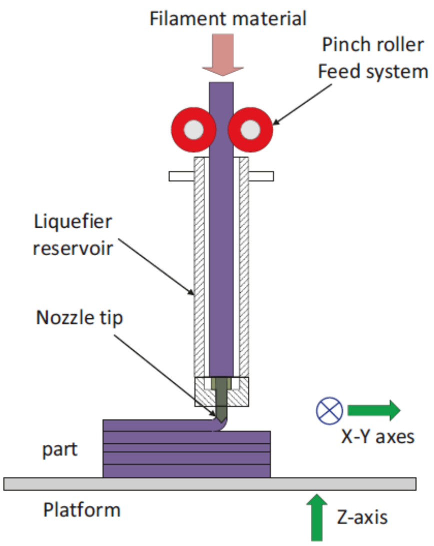



Figure A.1. Principle of material extrusion (Gibson et al., 2021).

**Vat photopolymerization** is an AM technology where UV light, usually provided by a laser, is used to cure liquid resin layer by layer. The UV light beam scans the surface of the liquid forming the desired pattern in each layer. The print is attached to a build platform which ascends and descends between each layer as a recoater levels the surface of the resin between each layer. This is repeated until the part is printed fully. Depending on the type of the equipment, the print can be formed from bottom-to-up or vice versa. This technology is also known as liquid-based additive manufacturing. Materials used in vat photopolymerization are photopolymers, developed in the late 1960s. Where thermoplastic polymers, used in material extrusion, can be melted and solidified over and over since they are linear or branched molecular structure, photopolymers are cross-linked in structure and they do not melt. In addition, they are not so sensitive to creep and show less stress relaxation. The materials (liquid resins) are either acrylate-based or epoxide-based. Acrylates react very well to curing but the strength of the parts is weaker due to shrinkage and curling. Epoxides form accurate, hard and stronger parts compared to acrylate resins (Gibson et al., 2021; Diegel et al., 2020).

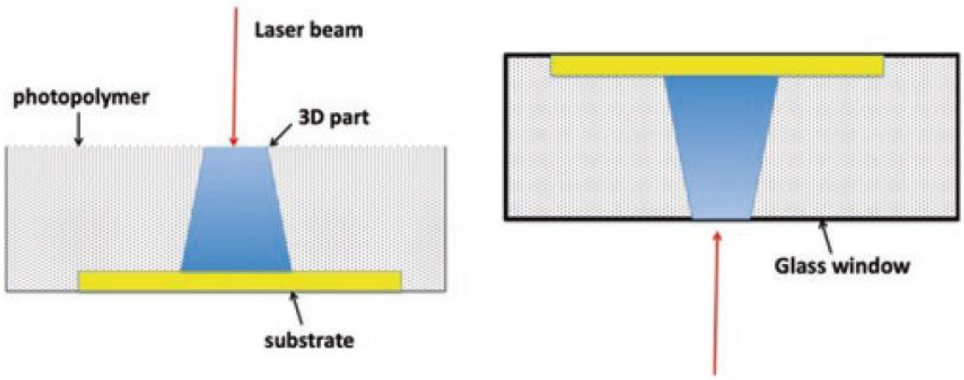



Figure A.2. Principle of VAT photopolymerization (Kumar, 2020).

**Material jetting (MJ**) is an AM technology with roots in traditional ink-head printing. The material is distributed from the printing head as droplets onto the substrate leading to the desired form. Materials, like waxy polymers or acrylic photopolymers are mainly used in the process. Other polymers, ceramics and metals are also under research for possible mainstream use in MJ. The main materials like wax solidify at room temperature after printing but when using photopolymer materials, ultraviolet light is used to polymerize the layer. This resembles VAT photopolymerization. The UV light source moves together with the printing head curing the material after jetting. Although the process seems to be simple, there are still several challenges to be faced in the technology since the forming of a three-dimensional object via jetting is a very complex process. The first issue is to get the solid material into liquid form. This leads to heating or using solvents/components in the material, which is a complex chemical process to handle. In addition, the jetted droplet requires special attention. The relationship between material, hardware and process parameters can be delicate, which directly affects droplet formation. (Gibson et al., 2021; Diegel et al., 2020).

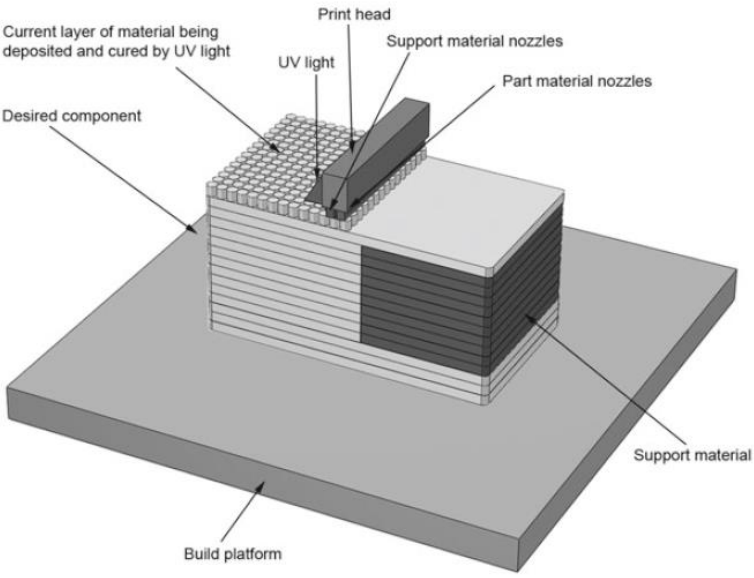



Figure A.3. Principle of material jetting technology (Diegel et al., 2020).

**Binder jetting** is an AM technology where a glue-like binder agent is deposited onto a powder bed through a nozzle in order to join the powder particles together. The powder material forms most of the printable objects as the binding agent forms only a small part of it. The binder is deposited as droplets making the powder particles and layers to bond to each other. After each layer, the powder bed moves down one layer height and the recoater distributes a new layer of powder. Due to the nature of the material, manufactured parts are mainly used for visual- or, light-duty functional prototyping and when using elastomeric infiltrant, printed parts can even be used in functional purposes. Infiltrants define what kind of properties the final part reaches. Infiltrants are usually acrylate-based (resembling Super Glue) or two-component infiltrants (EN-ISO ASTM52900, 2017; Gibson et al., 2021; Kumar, 2020).

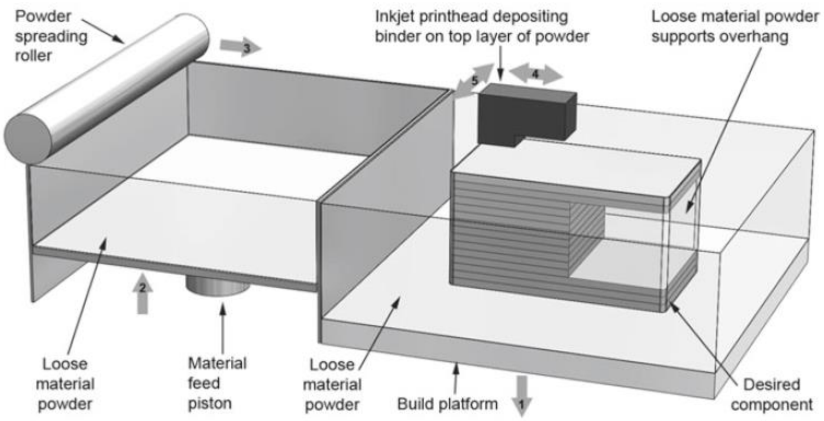



Figure A.4. Principle of binder jetting technology (Diegel et al., 2020).

**Powder bed fusion (PBF)** is a process in which the material (metal or polymer-based) is in a powder-like form in the bed. A laser is used together with scanning mirrors to direct the laser beam to the surface of the bed. The beam fuses the particles (with polymer materials) or melts them together (with metal materials) forming the desired pattern on the bed layer. The bed moves down one layer thickness (typically 0.075 – 0.1mm) and a counter-rotating levelling roller distributes a new layer of powder on top of the previous one. The beam again fuses the particles and also the layers together. This way, the part is manufactured inside the powder bed. The excess powder from the print work is collected, e.g. with a vacuum and processed if necessary. The technology uses sintering, hence the names polymer laser sintering (pLS) and metal laser sintering (mLS) (Gibson et al., 2021; Ngo et al., 2018).

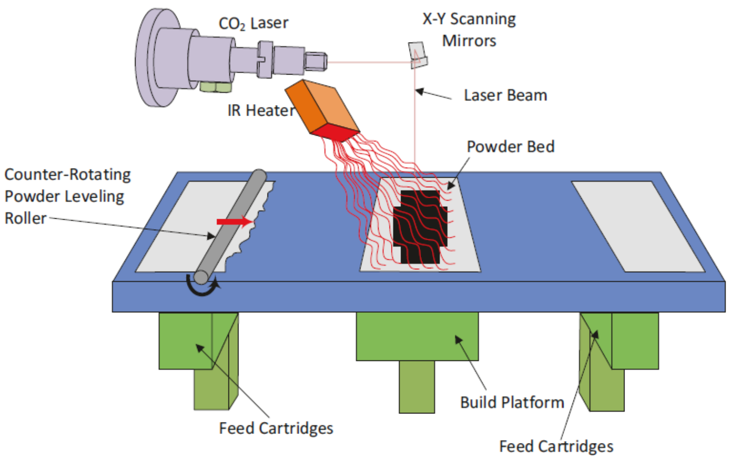



Figure A.5. Principle of powder bed fusion (Gibson et al., 2021).

**Direct energy deposition (DED)** is an AM technology based on melting material during deposition. In DED, heat energy is focused on small area of the substrate which melts the substrate, and at the same time, melts the material which is deposited onto the substrate's melted pool of material. The energy source is typically a laser or an electron beam (EN-ISO ASTM52900, 2017; Gibson et al., 2021)

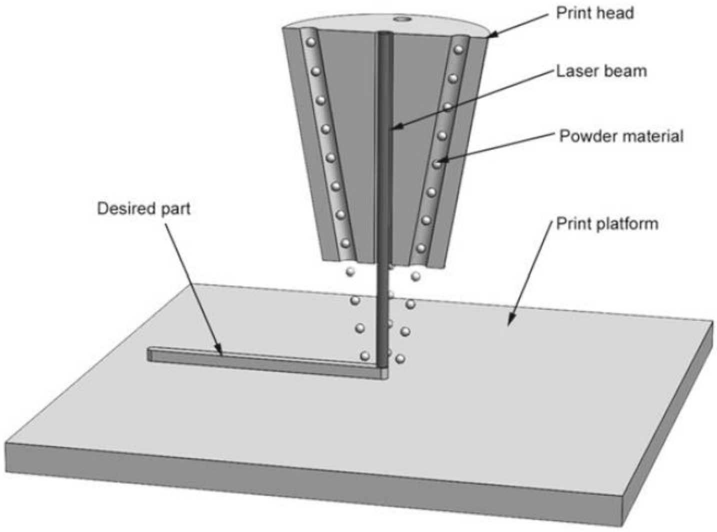



Figure A.6. Principle of directed energy deposition (Diegel et al., 2020).

**Sheet lamination** is probably the lesser known of the AM technologies. In this technology, paper material sheets are laminated together, layer-by-layer, with gluing or another adhesive bonging agent. Thermal bonding, clamping and ultrasonic welding can also be used to bring the sheets together. A mechanical cutter or a $CO_2$ laser is used to cut during each layer according to designed contours in order to make the final part layer by layer. The cutting is a very precise part of the process since it has to happen always one-layer depth at a time. The material that is left outside the contour acts as support material and it is diced with a crosshatching pattern in order to facilitate the removal of unnecessary paper material. In the post-processing phase, the whole object is usually warmed in an oven to facilitate the removal of the object and also the cube-like excess material. The technology is the bond-then-form type and therefore has many advantages such as minimal shrinkage, residual stresses or distortion problems (Gibson et al., 2021; Ngo et al., 2018)

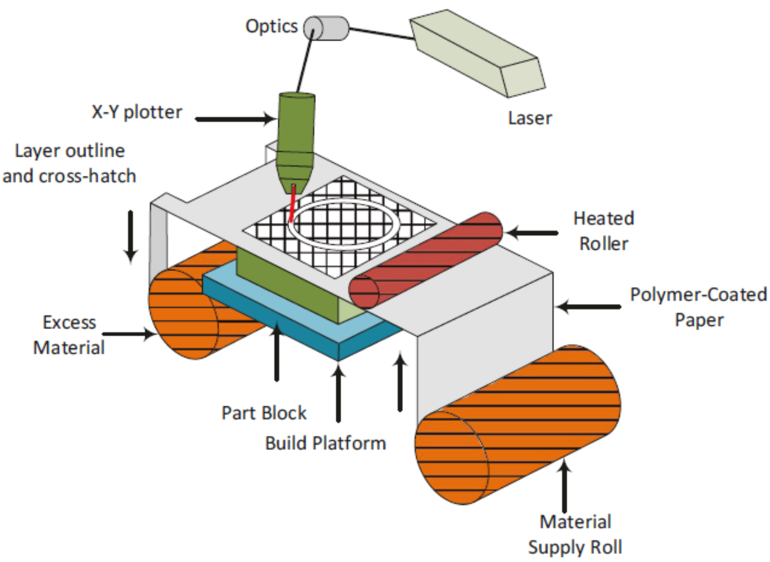



Figure A.7. Principle of sheet lamination (Gibson et al., 2021).

# Appendix B: Work-life questionnaire

LAPIN AMK
Lapland University of Applied Sciences

My name is Ari Pikkarainen and I work as a senior lecturer in the Lapland University of Applied Sciences mechanical engineering degree programme. I am doing my dissertation work currently for LUT University regarding the teaching and learning of 3D printing. The goal is to create a new kind of learning methodology for 3D printing in mechanical engineering education. In addition, the use of 3D printing in companies and industrial functions is researched. This will generate a view to the needs and requirements coming from work-life to the teaching of 3D printing in Lapland UAS mechanical engineering degree.
The results from the questionnaire will be dealt with anonymously and they are only for the internal use of Lapland UAS, company details will not be published.
Answering takes ca. 5 minutes and the responses are very important to the education of mechanical engineers at Lapland UAS regarding 3D printing.
You can direct this questionnaire to other responders in your organization, if necessary.
Thank you for your responses!

The questionnaire is done with Webpropol software, Lapland UAS information registry rules:
https://julkiset.lapinamk.fi/DropOffLibrary/Tietosuojailmoitus%20webropol.pdf

**1. Number of employees in your company ***

- ◯ Under 10
- ◯ 10 - 50
- ◯ 50 - 250
- ◯ Over 250

**2. Does your company use 3D printing services? ***

- ◯ Yes
- ◯ No

**3. 3D printing services used by the company ***

- [ ] Optimization of 3D models
- [ ] Design work
- [ ] 3D printing
- [ ] Post-processinf of prints
- [ ] 3D scanning
- [ ] Other (specify if necessary) ____________

**4. Does your company produce 3D printing services? ***

- ( ) Yes
- ( ) No

**5. 3D printing services produced by the company ***

- [ ] Design work
- [ ] 3D printing
- [ ] 3D printing education service
- [ ] 3D printer sales
- [ ] 3D scanning
- [ ] Other (specify, if necessary) ____________

**6. Does your company need information about 3D printing and its principles in the functions of the company? ***

- ( ) Yes
- ( ) No

**7. Information needed by the company about 3D printing** *

- ☐ Design principles of 3D printing
- ☐ 3D printing technologies and materials
- ☐ Possibilities of 3D printing in the functions of the company
- ☐ 3D printing price factors
- ☐ Other (specify, if necessary) ______

**8. How important are the following issues in engineering education?**

**Learning the principles of 3D printing (technologies, principles, process)?** *

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very important |

○ I don´t know

**9. 3D printing of polymers and the possibilities?** *

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very important |

○ I don´t know

**10. 3D printing of metals and the possibilities?** *

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very important |

○ I don´t know

**11. Knowledge from polymer materials in 3D printing? ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very important |

◯ I don´t know

**12. Knowledge from metal materials in 3D printing? ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very important |

◯ I don´t know

**13. Knowledge from composite materials in 3D printing? ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very important |

◯ I don´t know

**14. Practical exercises from polymer 3D printing? ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very important |

◯ I don´t know

**15. Practical exercises from metal 3D printing? ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very important |

◯ I don´t know

**16. Design principles in 3D printing? ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very important |

◯ I don´t know

**17. Optimization of 3D models (e.g. part consolidation, topology optimization)? ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very important |

◯ I don´t know

**18. Possibilities to use 3D printing in company operations and functions? ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very important |

◯ I don´t know

**19. Possibilities to use 3D printing in industrial functions? ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very important |
| | ◯ I don´t know | | | | | | | | | | | |

**20. The definition of profitability of 3D printing in product manufacturing? ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very important |
| | ◯ I don´t know | | | | | | | | | | | |

**21. Common 3D printing projects between companies and egineering education? ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very important |
| | ◯ I don´t know | | | | | | | | | | | |

**22. The recycling of 3D printed products and materials? ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very important |
| | ◯ I don´t know | | | | | | | | | | | |

**23. Re-manufacturing of products through 3D printing (circular economy)? ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Not important | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very important |

◯ I don´t know

**24. Free write: What kinds of knowledge will engineers require in the future concerning the use of 3D printing in companies / industrial functions?**

# Appendix C: Student questionnaire

LAPIN AMK
Lapland University of Applied Sciences

Greetings!

This questionnaire is part of the Spring 2020 "3D printing and applications" and Fall 2020 "Future technology" courses.
The goal is to map and analyse your learning concerning the use of multiple 3D printing technologies (FDM, SLA and SLS).
The results are used in the development of Lapland UAS 3D printing studies and in my dissertation for LUT University. The topic of my dissertation is research and development of learning 3D printing. The goal is to create a new methodology for learning 3D printing which can be used in engineering education in universities and universities of applied sciences.

The questionnaire will be done anonymously, the responses cannot be connected to the responder.

Thank you for your answers!

The questionnaire is arranged with Webpropol, Lapland UAS information registry

**1. Your expectations for the course** *

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Minor | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Great |

**2. The results from the course vs. expectations** *

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Failed | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Succesfull |

**3. What was your knowledge level BEFORE the course concerning 3D printing?** *

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Weak | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very good |

**4. What was your knowledge level AFTER the course concerning 3D printing?** *

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Weak | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very good |

**5. The introduction of FDM equipment (Ultimaker, Prusa ja Creality)** *

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easy | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Difficult |

**6. The introduction of SLA equipment (FORM3 and post processing equipment) ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easy | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Difficult |

**7. The introduction of SLS equipment (SINTERIT LISA PRO and post processing equipment) ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easy | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Difficult |

**8. Use of software for FDM (Cura, Prusa Slicer) ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easy | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Difficult |

**9. Use of software for SLA (PreFORM) ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easy | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Difficult |

**10. Use of software for SLS (SINTERIT Studio) ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easy | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Difficult |

**11. Design and principles of FDM (material extrusion) ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easy | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Difficult |

**12. Design and principles of SLA (vat photopolymerisation) ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easy | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Difficult |

**13. Design and principles of SLS (powder bed fusion of polymers) ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easy | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Difficult |

**14. Learning threshold and use of FDM ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easy | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Difficult |

**15. Learning threshold and use of SLA ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easy | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Difficult |

**16. Learning treshold and use of SLS ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easy | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Difficult |

**17. The use of the new AM process selection model ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easy | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Difficult |

**18. The simultaneous use of three technologies vs. the use of just one ***

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Easy | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Difficult |

**19. What is your experience using multiple 3D printing technologies simultaneously? ***

**20. Does the simultaneous usage of multiple 3DP technologies strenghter / weaken the learning of 3DP? Please justify your answer. ***

**21. How did you feel about the development of your skills during the course (learning process)? ***

**22. Did the AM process selection model help you in selecting the suitable technology for printing? (How ? Possible improvements?) ***

**23. What did each different technology (FDM, SLA, SLS) contribute to the learning of 3D printing? ***

**24. What was the most difficult thing in learning and using the technologies (name according to each technology)? ***

**25. Suggestions for improving the course? ***

**26. Free write and general opinions ***

# Appendix D: Drafted learning outcomes from the numerical responses

| QUESTION TOPIC = COMPETENCE<br>Average > 8.0 | CATEGORY | LEARNING OUTCOME<br>(The student...) |
|---|---|---|
| 1. Basics of 3D printing<br>- AM technologies<br>- AM principles<br>- AM process | KNOWLEDGE<br>KNOWLEDGE<br>COMPREHENSION<br><br>EVALUATION | Can identify different AM technologies<br>Can define the AM principles<br>Is able to compare AM processes and distinguish them from each other<br>Can select the most suitable AM process for application |
| 2. 3D printing of metals<br>- technology, possibilities | KNOWLEDGE<br>COMPREHENSION | Can identify the possibilities of metal 3DP<br>Understands the basics of metal 3DP<br>Can differentiate metal 3DP from polymer 3DP |
| 3. Design principles (DfAM) | COMPREHENSION<br>APPLICATION | Understands the meaning of DfAM in design work<br>Can apply the DfAM principles in design work |
| 4. Optimization of 3D models (e.g. topology optimization, part consolidation) | COMPREHENSION<br>APPLICATION<br>ANALYSIS<br>SYNTHESIS | Understands the meaning of structural optimization in AM<br>Can perform str.opt. based on engineering design principles<br>Can distinguish the targets for optimization<br>Can design optimized structures for AM |
| 5. AM in companies<br>- utilization in company functions | EVALUATION | Is able to perceive the possibilities of utilizing AM in company functions |
| 6. Viability of 3D printing<br>Definition in the product manufacturing process | KNOWLEDGE<br>COMPREHENSION<br><br>SYNTHESIS<br>EVALUATION | Can define the viability in 3D printing<br>Understands the cost structure of AM and its relationship with viability in product manufacturing<br>Can develop profitable parts through AM<br>Can compare the different AM technologies cost-wise |

| QUESTION TOPIC = COMPETENCE<br>Average < 8.0 | CATEGORY | LEARNING OUTCOME<br>(The student...) |
|---|---|---|
| 7. 3D printing of polymers<br>- technologies<br>- possibilities | KNOWLEDGE<br>COMPREHENSION | Can identify the possibilities of polymer 3DP<br>Understands the basics of polymer 3DP<br>Can differentiate polymer 3DP from metal 3DP |
| 8. Practical exercises<br>- polymer / metal 3DP | APPLICATION<br>ANALYSIS | Is able to use selected AM technology independently<br>Can choose the most suitable AM technology for printing |
| 9. Project learning<br>- common projects between education and companies | SYNTHESIS<br>EVALUATION | Can adapt the AM principles into real-life projects<br>Is able to compare the produced solutions and select the best alternative |
| 10. Recycling<br>- 3D printed parts and materials | KNOWLEDGE<br><br>COMPREHENSION | Recognizes different polymer materials and usage purposes for 3D printing<br>Understands the principle of recycling polymer 3D printed objects and filament fabrication |
| 11. Re-manufacturing (circular economy) | COMPREHENSION<br>ANALYSIS<br>SYNTHESIS | Understands the meaning of re-manufacturing of products<br>Can point out the possibility for re-manufacturing<br>Can design products according to the re-manufacturing principles |

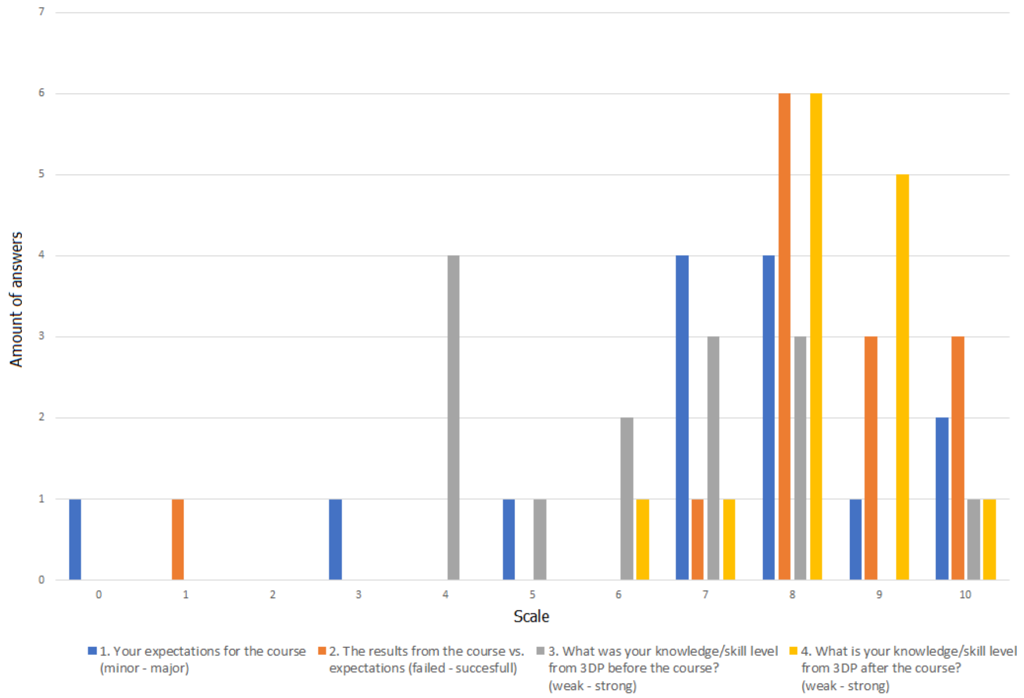
| QUESTION TOPIC = Free word | CATEGORY | LEARNING OUTCOME<br>(The student...) |
|---|---|---|
| 12. 3D printing in engineering<br>- as a part of traditional mechanical engineering<br>- possibilities and limitations<br>- distinguish different applications<br>- reflecting into real situations (e.g into function principles of machines) | COMPREHENSION<br>COMPREHENSION<br>APPLICATION<br><br>ANALYSIS<br><br>ANALYSIS<br><br>SYNTHESIS<br><br>SYNTHESIS | Can illustrate mechanical functions through 3DP<br>Understands the possibilities and limitations of 3DP<br>Can identify the possibilities and limitations of 3DP in mechanical engineering<br>Can distinguish 3DP as a manufacturing method from the traditional ones<br>Can distinguish different 3DP applications (prototyping, small series, mass production)<br>Can combine 3DP into traditional mechanical engineering topics<br>Can adapt 3DP into real situations (e.g. mechanical functions) |
| 13. 3D printing and life-cycle<br>- spare parts and product life-cycle | COMPREHENSION<br>APPLICATION | Understands the role of 3DP in part life-cycle<br>Can identify the targets for spare part production through 3DP |
| 14. 3D scanning knowhow<br>- basic understanding and applications | COMPREHENSION<br><br>APPLICATION<br>SYNTHESIS | Understands the principle and possibilities of 3D scanning in 3DP<br>Can use 3D scanning in the production of data for 3DP<br>Can compile and covert 3D scan data into a format for 3DP |

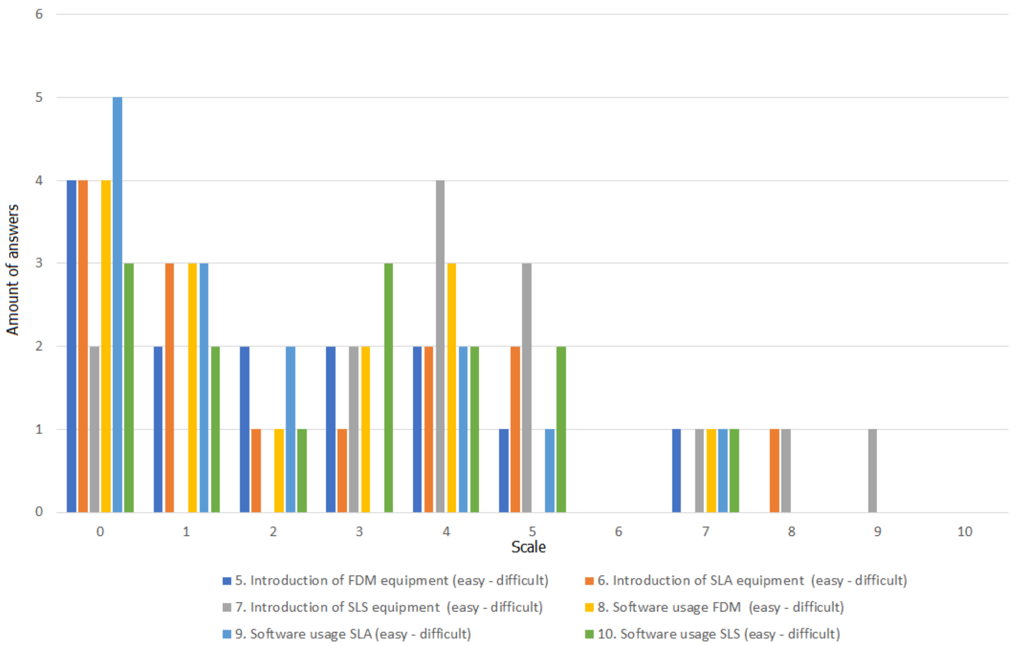
# Appendix E: Competence matrix for AM education

| Semester | Competence matrix | 1. Basics of 3D printing | 2. 3D printing of metals (theory in Lapland UAS) | 3. Design principles (DfAM) | 4. Optimization of 3D models | 5. AM in companies and industry | 6. Viability of 3D printing | 7. 3D printing of polymers | 8. Practical exercises | 9. Project learning | 10. Recycling | 11. Re-manufacturing | 12. 3D printing in engineering | 13. 3D printing and life-cycle | 14. 3D scanning know-how |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | Project: Product Development | x | | x | | | | x | | | | | x | | |
| 3 or 4 | 3D printing (book exam) | x | x | x | | | x | x | | | | | x | x | |
| 4 | Project: Prototype | x | | x | | | | x | x | | | | x | | |
| 4 | 3D Design of a product | x | | x | | | | x | x | | | x | x | x | |
| 5 | Work-life project | | | x | x | x | x | x | | x | | | | | |
| 6 | Project: Finding solution | x | | x | x | x | x | x | x | x | | x | x | | x |
| 6 | 3D Printing and applications | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| 7 | Project: Innovation | | | | x | x | x | | | x | x | x | x | x | x |
| 7 | Future technology | | | | x | x | x | | x | x | x | x | x | x | x |
| 8 | Bachelor thesis | x | x | x | x | x | x | x | x | x | x | x | x | x | x |

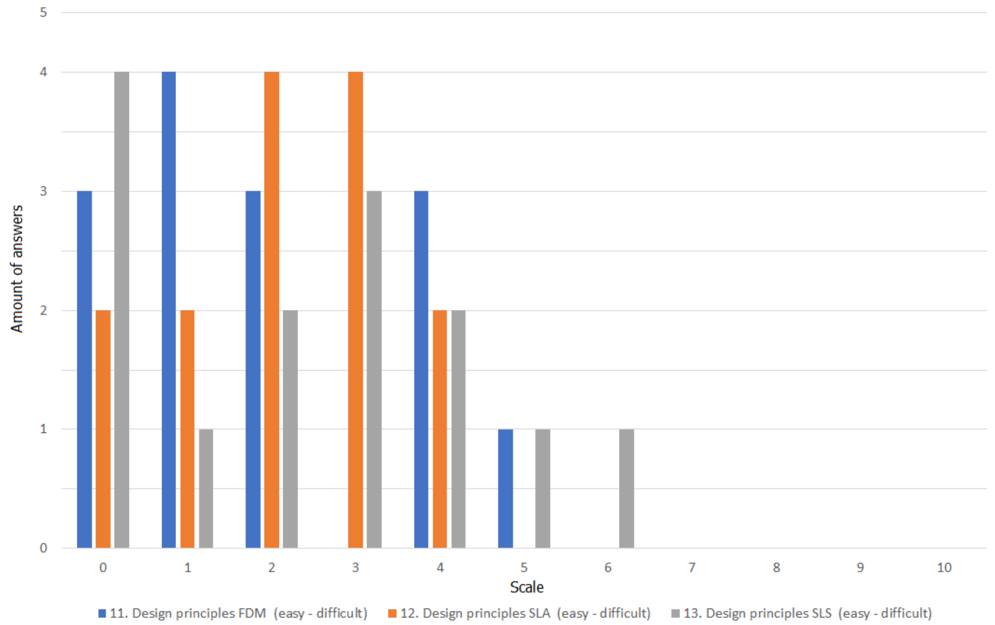
This table presents the AM-related courses in the curriculum of Lapland UAS mechanical engineering. More detailed description of the number of ECTS credits and learning types can be seen in P4. The competence areas in the horizontal section are based on the topics from the questionnaire. The AM courses and semesters in the vertical section are linked to the competence areas. The green arrow presents the path to more advanced courses as the semesters proceed. When the competence matrix was done, the learning outcomes from each of the competence areas were added to the course descriptions and evaluation criteria. For example, the first courses such as "Project: Product development", present simpler topics from AM and the initial section of the Bloom´s taxonomy (knowledge, comprehension and application). The course description can contain the learning outcomes as follows: *"The student can identify different AM technologies and is able to compare the processes and distinguish them from each other. The student can apply the DfAM principles in design work and understand the meaning of structural optimization in AM".* The learning outcomes help in identifying the outcome for the learning and in addition, in the recognition of know-how if the student, e.g. applies for credits based on earlier studies.

# Appendix F: Results from the student questionnaire

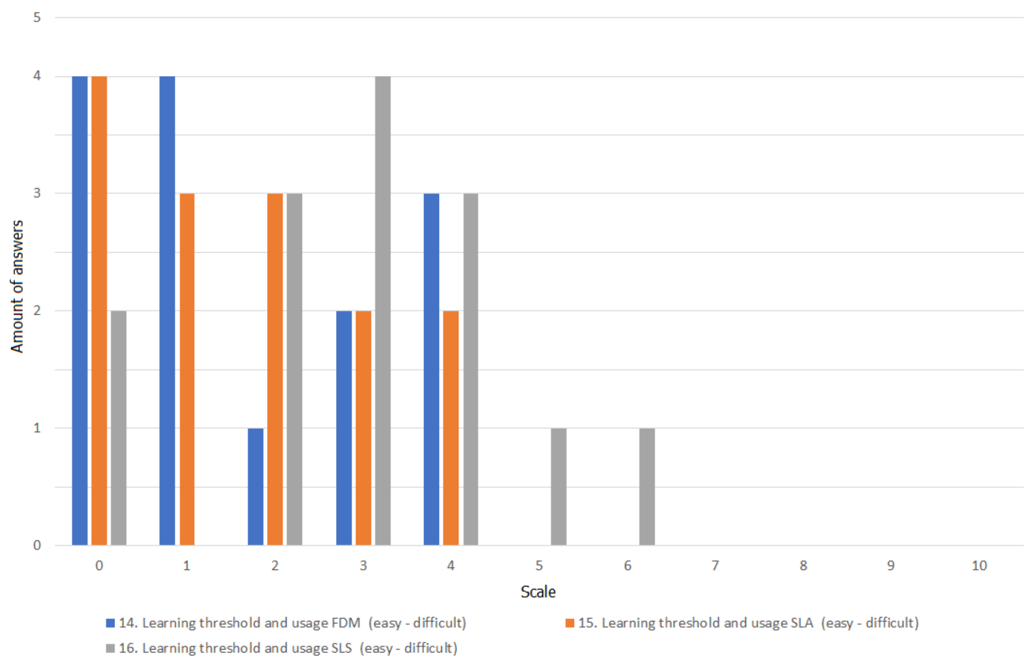


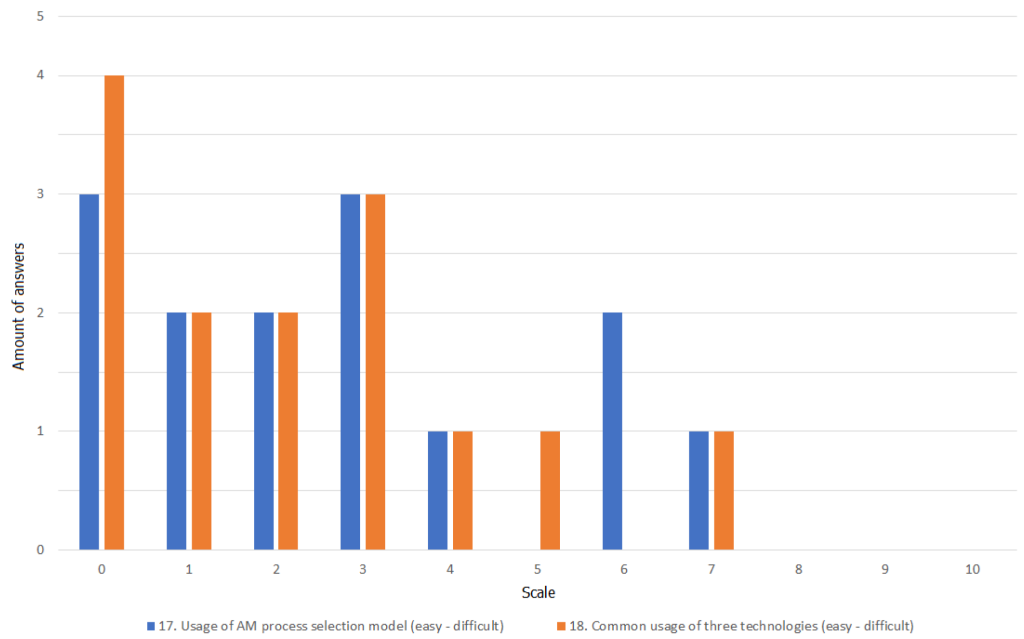


Amount of answers
6
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10
Scale
5. Introduction of FDM equipment (easy - difficult)
6. Introduction of SLA equipment (easy - difficult)
7. Introduction of SLS equipment (easy - difficult)
8. Software usage FDM (easy - difficult)
9. Software usage SLA (easy - difficult)
10. Software usage SLS (easy - difficult)

Amount of answers
5
4
3
2
1
0
0 1 2 3 4 5 6 7 8 9 10
Scale
11. Design principles FDM (easy - difficult)
12. Design principles SLA (easy - difficult)
13. Design principles SLS (easy - difficult)


5
4
3
2
1
0
Amount of answers
0
1
2
3
4
5
6
7
8
9
10
Scale
14. Learning threshold and usage FDM (easy - difficult)
15. Learning threshold and usage SLA (easy - difficult)
16. Learning threshold and usage SLS (easy - difficult)


5
4
3
2
1
0
Amount of answers
0
1
2
3
4
5
6
7
8
9
10
Scale
17. Usage of AM process selection model (easy - difficult)
18. Common usage of three technologies (easy - difficult)

# Publication I

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**Creating learning environment connecting engineering design and 3D printing**

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# Creating learning environment connecting engineering design and 3D printing

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**Abstract**

Engineering education in modern days require continuous development in didactics, pedagogics and used practical methods. 3D printing provides excellent opportunity to connect different engineering areas into practice and produce learning by doing applications. The 3D-printing technology used in this study is FDM (Fused deposition modeling). FDM is the most used 3D-printing technology by commercial numbers at the moment and the qualities of the technology makes it popular especially in academic environments. For achieving the best result possible, students will incorporate the principles of DFAM (Design for additive manufacturing) into their engineering design studies together with 3D printing.

This paper presents a plan for creating learning environment for mechanical engineering students combining the aspects of engineering design, 3D-CAD learning and AM (additive manufacturing). As a result, process charts for carrying out the 3D printing process from technological point of view and design process for AM from engineering design point of view were created. These charts are used in engineering design education. The learning environment is developed to work also as a platform for Bachelor theses, work-training environment for students, prototyping service centre for cooperation partners and source of information for mechanical engineering education in Lapland University of Applied Sciences.


Peer-review under responsibility of the scientific committee of the Nordic Laser Materials Processing Conference 2017

*Keywords:* 3D printing, fused deposition modeling, design for additive manufacturing, engineering design, learning environment

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## 1. Introduction

Engineering education require different methods to combine traditional theory-based learning into hands-on learning. Additive manufacturing (AM) offers a great opportunity to connect practical work into different engineering areas. Different AM technologies enable numerous applications to harness engineering thinking into practice. Engineering design is based on general product development process and it is combined to the generic AM process chain in order to create new way to look AM product design cycle from learning point of view. The generic product development model offers clear start to the new model since it consists of sequential steps covering the process all the way from planning phase to production ramp-up. The model gives the foundation to the design process also from the learning point of view when conceiving, designing and realization are the main actions in the process. (Ulrich et al. 2008.)

Fused deposition modeling (FDM) is the most popular AM technology at the moment even measured by commercial numbers and it offers clear way to harness AM technology into engineering (Aniwaa 2016; Gibson et al. 2015). Even though AM and especially FDM is highly popular now, the learning side of the technology requires continuous investigation and development. The growing demand from the industry towards engineering education requires new kind of thinking in both teaching and learning. Modern engineers need to be skilled in participation and especially in a process, which will lead into the birth of new processes, products and projects. This requires different innovative methods in engineering education, which support the technical and theoretical expertise of an engineering student. (Crawley et al. 2014.) One important factor in AM in to apply the basics of DFAM principle (Design for additive manufacturing). DFAM is a design principle, which redefines the design guidelines especially for AM technologies. It enables the designing of printable object and takes into consideration all the necessary possibilities and limitations of used AM technology. (Thompson et al. 2016; Gibson et al. 2015.)

The aim and purpose of this study is to create a learning environment for mechanical engineering students in Lapland University of Applied Sciences in Finland (Lapland UAS), which combines traditional engineering design and additive manufacturing. For efficient learning of AM technologies, different process charts for learning purposes were created as the platform for the environment.

## 2. Creating learning environment

The creation of the learning environment is based on the studies provided by the mechanical engineering degree in Lapland UAS. One of the key factors in the degree is traditional engineering design, which combines several course contents into practice. Engineering design forms one way for the students to practice their skill in real-life situation by performing different customer projects. This is used as a starting point in creating the new learning environment in which AM in introduced to the functions of the existing operation. The principle of engineering design environment is presented in figure 1.

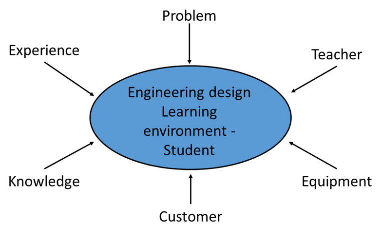


Fig. 1. Principle of engineering design learning environment.

In the creation of the new learning environment, necessary factors were recognized and developed to function in the environment. The new environment contains possibility to handle and solve problems, perform design tasks through development and/or customer works, use 3D printing equipment as practical method and use own learned skills and experience. The structure of the created learning environment consists of following factors, which were developed:

- Description of the active learning in the environment
- Simplified 3D printing process chart
- New model for AM design process
- Learning assignment process charts
- Learning environment future development purposes

### *2.1. Description of active learning in the environment*

In order to create a functional learning environment, different learning factors had to be recognized. The traditional engineering way has leaned heavily on behavioristic learning in the past but modern engineering education uses more participatory pedagogics. From this, a model of active learning method was created. This was used in the development of the learning environment and it gives a perspective what are the important factors in learning. Model of active learning consists of six different factors as follows and can it can be seen in figure 2:

- Background knowledge: knowledge provided by the mechanical engineering degree studies and the basics of DFAM
- Practical exercises: practical laboratory exercises with 3D printers; partially guided, partially fully independent work, students can perform their own projects and learn more
- Supporting lectures: support and introduction lectures about the technology and process
- Teacher tutoring: teacher works as a tutor during the printing and gives guidance and support
- Equipment introduction: introduction of the printers and especially the safety guidelines in printing
- Time planning and use: concerning independent work, the student must plan his or hers own time usage between theoretical and practical learning; the model requires unprompted work from the student

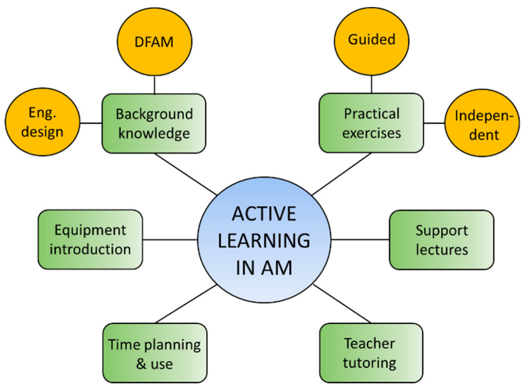


Fig. 2. Active learning in AM.

## *2.2. Simplified 3D printing process chart*

The FDM printers used in the learning environment were acquired from Finnish manufacturer Minifactory Oy Ltd. The company provides two different models, Education 3 and Innovator. The latter is used in the study since Innovator model enables easier way to use the technology whereas Education 3 model requires a bit more investigation. Minifactory has a website containing separate Kampus-section that provides informative instruction videos for introduction of the printers. Kampus is used in the environment as a source of information for flipped learning methods in the learning environment.

A simplified printing process chart was derived from the generic AM process chart and it is used in the learning assignments done in the environment. This introduces the printers to the students and helps them to separate all the necessary stages in order to perform the print. First stage is the actual 3D modeling. This will contain the engineering design and DFAM perspective. The model file is transferred to the slicing software Repertier-Host that is used with the Minifactory printers. This plays a big role in the environment since one important phase is to learn to use the software. After this, the student prepares the printer in the practical stage. This requires the equipment introduction so that the student is able to perform this stage even independently. The printing itself takes place along with proper follow-up to the process. The last stage is to post-process the print and evaluate the result. The process chart enables iteration in different stages in order to achieve the best result possible. This demands continuous evaluation from the student in different stages of the process. The printing process chart is shown in figure 3.

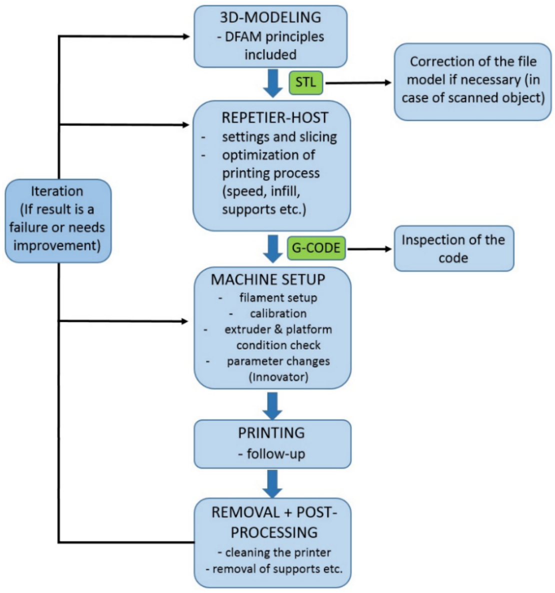


Fig. 3. Simplified AM printing process

### 2.3. New AM design process model

Integration of traditional engineering design and AM requires new kind of approach. Usually the design process is done according to generic product design process, which studies the process from the product's point of view. Additive manufacturing is usually seen as a phase in the product development process, which offers the possibility to produce prototypes. When considering engineering design education, AM point of view must be integrated to the model in order to have the full advantage of the technology. This enables to use the process model in a way that utilizes the AM basics from the start and gives the full advantage of the technology to be used in the design process. Model can also be used plainly for designing 3D printable products, which is the usual way to investigate AM process models. In the model, the active learning and AM printing process are shown in their own places. This model helps the student to follow the AM design process, realize the factors of active learning in the beginning, and use the 3D printing process model in the practical stage. The AM design process model can be seen in figure 4.

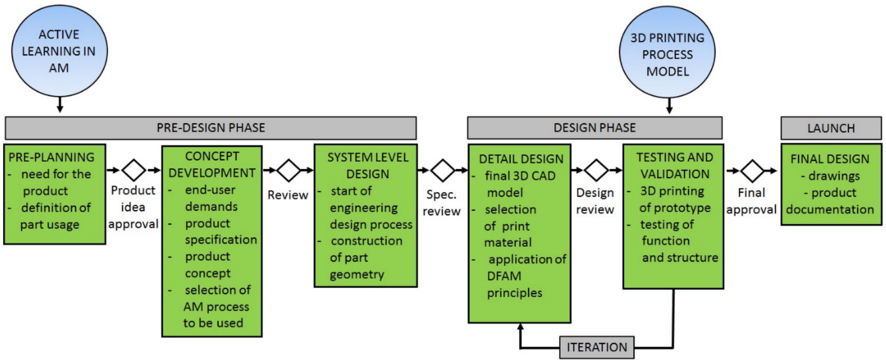


Fig. 4. AM product design process model.

### 2.4. Learning assignments

The first stage in introducing the learning environment to mechanical engineering students is to approach AM technologies through learning assignments. The learning process is divided into two sections in which the first offers the basics of AM knowledge while the second concentrates to practical work. Assignments can be used in an academic institution as a part of the degree courses or e.g. for training groups outside the institution without actual evaluation with grade. The main topics covered in the first assignment are:

- Introduction of AM and the basic principles
- General AM manufacturing process
- Presentation of different AM technologies
- Post-processing of the print
- DFAM basics
- New improved AM design process model and printing process chart

The first learning assignment consists of introduction lecture, flipped learning and learning portfolio. Flipped learning is a pedagogical approach, which leans on to the independent learning done by the student. The student can regulate his/hers own learning and learning is not dependent on the teacher. (Toivola, Silfverberg 2016.) This encourages the student to act independently as where the teacher acts as a mentor to the learning through learning materials and contents (FLN 2014). The introduction lecture presents the structure of the assignment and offers the basic information behind AM technologies and in this case, especially from FDM technology. It also presents the different process charts created for this purpose (active learning-, 3D printing process- and AM product design models). After this, the student investigates independently given topics by browsing given source of information. In this study, a website called 3D Hubs.com was used since it offers good and usable information from required topics. The student has to write a learning portfolio in which he/she reflects what was learned from given topics. The portfolio is returned for evaluation to the teacher. After this, an evaluation discussion is held with the students in which teacher gives feedback from the portfolio and the evaluation is based on accepted/failed. The feedback system is used to ensure that the student receives information about the strengths and weaknesses in their own knowledge. If the student's portfolio and discussion is accepted, he/she can proceed to the second assignment. This ensures that the student has sufficient knowledge to proceed into the practical stage so the student received "a driving license" to use the printers. If the student fails, the feedback is used to show necessary points to be repeated in order to earn the accepted-status. The model of the first assignment is presented in figure 5.

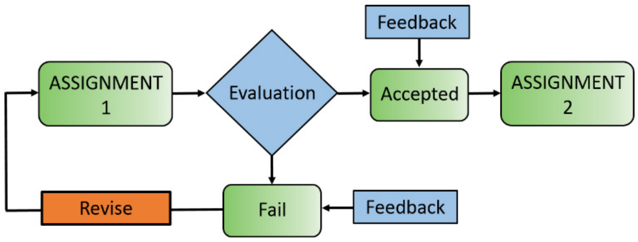


Fig. 5. Learning assignment 1 model.

After passing the first assignment, the student proceeds to the second learning assignment. This is used for giving a grade if assignments are used as course tasks in a university or similar academic institution. The second assignment introduces the AM product design process in which the student design a printable object. The assignment is divided into following sections and it is presented in figure 6:

- Recognizing the need and drafting the idea for the part; the need comes from the student
- Designing and modeling of the part; usage of 3D modeling software and -scanning
- Orientation lecture about the printers; presentation of the printers
- Working and safety issues
- Printer setup and printing process
- Post-processing of the part and printer (e.g. removal of supports, printer cleaning)
- Inspection of the part; comparison to the original design (measurements and forms)
- Result evaluation and recognizing possible need for iteration; presenting the result to teacher
- Iteration; re-design and re-printing
- Final review of the part and conclusions; feedback discussion with the teacher

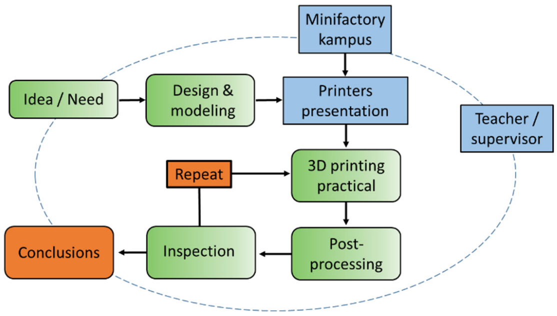


Fig. 6. Learning assignment 2 model.

Goal in the second assignment is that student is able to perform most of the stages independently while teacher works as a tutor and monitors the work from outside the process.

*2.5. Future of the learning environment*

The future of the learning environment requires continuous development. As in every environment, which leans on technology, here the state of the technology is in the center. Environment requires the acquisition of other AM technologies in the future such as stereolitography (SLA), material jetting and selective laser sintering (SLS) few to mention. This enables multiple different research possibilities between the technologies while FDM gives good foundation to the AM learning process. The learning assignments created for the study are the first step and the feedback, which will be gathered from the students, is used in further development of the learning assignments. The learning environment is meant to be used as versatile as possible and one development path is to use it as a prototyping environment as presented in figure 7.

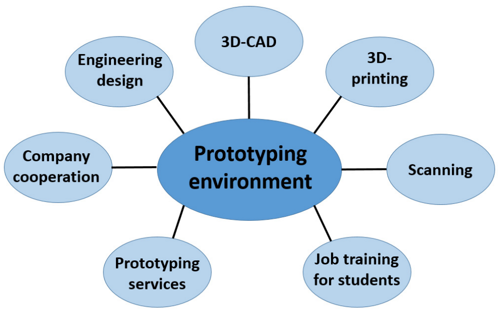


Fig. 7. Prototyping environment concept.

First, the environment would act as substrate for Bachelor theses, which will be used in developing the environment. The student point of view will be present this way and it ensures the functionality of the environment for learning purposes. The environment would combine aspects from engineering design, 3D CAD modeling, 3D printing and –scanning for different purposes such as by offering cooperation and prototyping services for collaboration collaborates and companies. It could also work as a job-training centre for student in where they could work by doing different tasks and projects. Students could even perform the mandatory work training required by the degree. From the learning point of view, the environment enables training possibilities for different target audiences and education partners, which would increase the awareness about AM. The learning environment could also offer fully independent learning possibility through flipped learning method combined to practical exercises.

### *2.6. Considerations of working with plastic vs. laser*

As presented in previous chapter, the learning environment could also include different printing technologies. The principle of the learning environment is open to all AM technologies and it is not attached to any certain technology although the structure would need some adjustment when moving into more demanding AM technologies.

FDM with plastic provides good starting point especially to educational units because of its relatively low price and simplicity of the technology. The environment would function well just with this technology. Next step could be to make the used technology in the environment a bit more versatile, which would offer more possibilities and research targets as the selection of technologies would increase. SLA (cured with laser) could offer the first step to introduce laser-based printers since its price is lower that e.g. in powder bed fusion (PBF) with laser in selective laser sintering (SLS). SLA would still keep the costs relatively low if the price is an obstacle in acquiring AM technologies to educational units while it would give more possibilities to design choices and equipment introduction. When moving into more complex laser printers and metal as a material, the demands and price increases. This would demand also some changes and additions to the contents of the learning environment. Working with laser/plastic (SLS) the price would be higher but interactions with plastic material would remain almost the same while achieving more accuracy and design choices. Working with laser/metal in e.g. direct metal laser sintering (DMLS) the price would be even more higher and this would also introduce some additions to DFAM principles presented to the students due to different nature of printing with metal. In this option, different requirements e.g. to build-time, equipment and post-processing have to be taken into account also.

In all of these cases, the basics of the learning environment will remain the same concerning the learning outcome of an engineering student. The learning will become more efficient and versatile while working with different technologies when the students can compare different features of different technologies. Learning outcome can also be targeted by using different AM technologies. The different process models of the learning environment can also be adjusted to match certain technology if needed since they are structured in generic form.

## 3. Conclusions

The aim and purpose of this study was to create a learning environment for mechanical engineering students at Lapland University of Applied Sciences in Finland combining 3D printing and engineering design. The study was carried out in collaboration with Laboratory of Laser Processing (LUT Laser) of Lappeenranta University of Technology. Functional learning environment requires different process models both from the technological and pedagogical point of view combined with 3D printing equipment. The learning aspect works through assignments, which ensure the level of knowledge and technical knowledge of the students for them to develop into experts in their own area. Learning environment requires continuous development in the future from both technological and pedagogical point of view in order to remain functional for the students. The nature of the learning environment is generic and can be therefore applied to different AM technologies and engineering educations.

### Acknowledgements

This study was carried out as a Master thesis done in Lapland University of Applied Sciences, Unit of Technology, Kemi, Finland and was done in collaboration with Laboratory of Laser Processing (LUT Laser) of Lappeenranta University of Technology. Authors would like to thank the personnel at LUT laser for their guidance in doing this study and Lapland University of Applied Sciences for enabling the Master thesis subject.

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# Publication II

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**Implementing 3D printing education through technical pedagogy and curriculum development**

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# Implementing 3D Printing Education Through Technical Pedagogy and Curriculum Development

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**Abstract**—This study presents the development of a new pedagogical method, namely the model of technical pedagogy, for learning additive manufacturing (AM) due to the speed of the technological development. The speed of the technological development of AM is faster than of the educational one; curricula and teaching methods have to evolve all the time in order to keep up with the development. The implementation of AM into the mechanical engineering curriculum in Lapland university of applied sciences (Lapland UAS) in Finland is used as an example in this study. The aim and purpose of this study is to create a model of technical pedagogy which gives universities the possibility to integrate AM into their curriculum more efficiently. This happens by combining traditional pedagogy into technical subjects in curriculum development work. This study also presents the learning concept of AM which shows the learning to be inversely proportional to the requirements of AM. Identification of the learning process of AM help the educators to plan AM education more efficiently.

**Keywords**—3D printing, additive manufacturing, pedagogy, technical pedagogy, curriculum, knowledge transfer

## 1 Introduction

Additive manufacturing (known also as 3D printing) is a technology where an object is built layer by layer from 3D CAD model with 3D printer [1]. 3D printing technologies are divided into seven different process categories according to the technology type and name according to SFS-EN ISO / ASTM 52900:2017 [2]. The process categories are binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization. Material extrusion is the most used one due to its relatively low price and easiness of use compared with other technologies [1]. 3D printing started in 1984 when Charles Hull invented and patented the stereolithographic principle where UV light was used in curing photopolymer liquid layer by layer. This was the origin of vat photopolymerization technology. It was soon followed by powder bed fusion in 1989 where selective laser sintering (known as powder bed fusion of polymers) was used to sinter polymer particles together. Scott Crump from Stratasys patented fused deposition modeling technology in 1992 which was the start of material extrusion technology. Material jetting technology has its roots from the middle of the 1990´s but the principle of jetting grew stronger especially by the development by the Objet Company in the 2000´s [1], [3]. These construct the basis of polymer printing technologies discussed in this study.

Perhaps the largest impact on modern desktop size 3D printing happened in 2009 when the patent for material extrusion expired. This was the start for a new generation of 3D printers and to the development of desktop size printers. This ensured AM to be a solid part of engineering and other types of applications [3]. For example, in engineering education, this meant that AM could be reckoned as one manufacturing alternative within the traditional ones such as milling and turning. This happened through the increased variety of AM machines, especially by cheaper desktop size 3D printers which could be acquired for educational purposes more easily.

In the field of mechanical engineering, 3D printing opens up a broad area for learning since education and proper training is a necessity especially for the students and experts, who work with 3D printing [4]. One main function of universities of applied sciences (UAS) in Finland is to produce professionals according to the work life demands and demands [5]. Therefore, 3D printing offers the possibility for UAS to offer proper and practical AM education for work-life purposes through the graduated engineers.

One key component in learning the required skills (e.g. AM) is to operate with problem-solving processes. This is because work-life consists of different phenomena and problems which have to be handled with using the skills. The reality which work-life demands brings to learning can be implemented through problem-based learning addressing the problems and situations. The problem-solving process is based on finding information from the problem and constructing possible answers to the problem [6]. According to the experience of main author, 3D printing presents an excellent way to learn technology since learning by doing and handling problems during the AM process produces knowledge that the students can exploit in work-life situations. For example, the mechanical engineering students at Lapland UAS have described the learning of 3D printing, which includes the theoretical and practical part, to be efficient especially when the student can perform independent tasks with printers. Finding the reason to some problem makes the learning more versatile.

The aim and purpose of this study is to create a model which will combine the traditional pedagogical aspect of learning into the technical factors that need to be considered when arranging technical education through curriculum development. Based on the experience of the authors, the practices for learning AM in engineering are generally unorganized, every university performs AM teaching in their own way. Therefore, a need exists for a pedagogical model based on AM learning. This forms the problem statement identified in this study.

The literature considering learning AM in engineering education does not provide a solid model which would take the technical aspects into consideration in the pedagogical arrangements. The model created in this study is called the ***model of technical pedagogy***. This model works as a guide for educators when planning or developing education around certain technology with more detailed technical issues. In addition, this study presents the implementation of AM into the curriculum of Lapland UAS mechanical engineering students and offers a view to inversely proportional learning of AM, which forms the foundation for understanding the implementation of AM education.

The theoretical information presented in this study work as a background for the model by justifying the usage of desktop size printer technology in engineering education due to its benefits (such as availability, price and suitability). Methodology used in this study is based on literature review and on the 13 years´ experience of the main author as an educator of mechanical engineers and to the student feedback received from past 3D printing courses in Lapland University of Applied Sciences in Finland (Lapland UAS). The implementation of AM to the curriculum is based on to the mechanical engineering curriculum development work done in Lapland UAS between 2014-2017. The technologies under discussion in this article are material extrusion, vat photopolymerization and powder bed fusion which present the most used technologies in the polymer/desktop size printer area. In addition, these represent the AM technologies used in current Lapland UAS mechanical engineering 3D printing laboratory.

### 1.1 Background for the study

This overview creates the background for the study since the classification of 3D printing equipment is important when planning AM education especially in engineering. This section separates industrial printers from office/desktop size printers since concerning AM education, the price and usability of the equipment are important in acquiring equipment for educational purposes.

A division between the printer types according to their size and usage can be seen in Figure 1 [7].

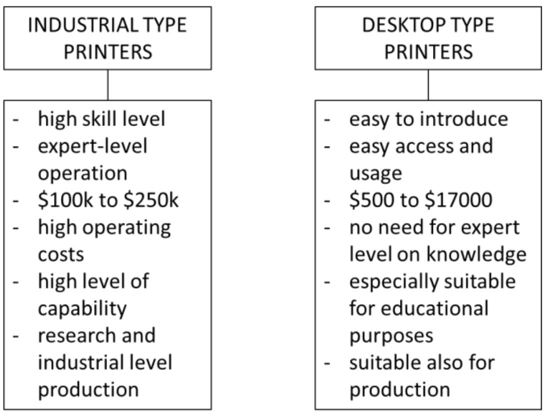


**Fig. 1.** AM printer type division [7]

This kind of division (see Figure 1) from the knowledge point of view is required in order to understand the requirements for using 3D printers. It is important to understand the requirements for educating engineers with AM contents. For example, it is important to make this division in engineering education when planning AM education from learning, usage or budget point of view. The technology should be accessible for the students and the threshold for learning and using it should be low in the beginning. This will be discussed later in this study as it presents the learning process in AM with respective to the requirements from the technology. This division (see Figure 1) helps in decision making when acquiring AM technology to the education. The differences between the types (see Figure 1) are discussed in following.

First group are so called conventional industrial type printers which are meant for professional use. Introduction of these printers requires a high skill level and the users are usually labeled as AM experts in their area. This higher level of technology cannot be used in the basic AM education of engineers due to the lack of experience of the students. The types of machines are not usually available for e.g. in student projects widely since it requires more knowledge, time and expertise to use these. These are very expensive, ranging from $100000 up to $250000 when discussing the base price of polymer printers. These devices need accessories so in total the price can reach $350 000. The operating costs are high and the machines are capable of industrial level of operation. The application is usually research, industrial level manufacturing or part of a manufacturing process. This shows that these types of machines are not necessarily the best option for adopting AM to engineering education. Especially when learning the basic principles of the technology is in the center. Therefore, the industrial type printers should be used in the final semesters of engineering and in more advanced student projects. The 3D printing projects are usually under a close inspection and reviewing which limits the user base. This means that the printing work is supervised and it cannot be used e.g. in independent student projects in earlier semesters. Therefore, the typical user is a last stage student with good experience with the machine, making his/her BSc (Bachelor of science) thesis or other research work. The 3D printers are usually placed in some sort of center of research or excellence [7].

Desktop level printers (see Figure 1) are targeted to normal consumers and regular users. This makes these types of 3D printers more suitable for engineering education when e.g. adopting AM to curriculum due to the lower use threshold of the technology. The lower price enables the acquisition of multiple printers and through this more students can be reached in courses. Desktop level printers are easy to use and they require low skill level in the beginning. Some printers such as the vat photopolymerization printer Form 3 from Formlabs require only a couple of minutes for start the printing work, even without less experience. Since the purchase price of desktop level printers is usually around 10% compared with the industrial type printers, user can acquire more than one printer. If one printer fails or has downtime, the work will not stop due to failure or maintenance etc. [7]. The price range is very wide for the desktop type printers: the cheapest material extrusion printers start from $500 and more advanced selective laser sintering printers are around $17000. This means that in education multiple printers can be used simultaneously and the entire student group can learn by doing at the same time without having to wait for available printer. This is important especially in the courses where AM in introduced to students; by connecting the theoretical lectures with practical work with the printers as soon as possible, the students are capable of connecting the AM knowledge into practice more efficiently. The development of AM technologies can be seen in Figure 2 [8].

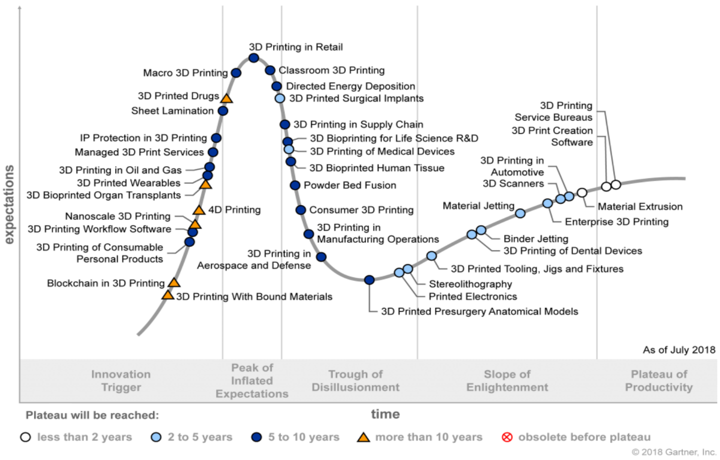


**Fig. 2.** Gartner hype cycle for 3D printing [8]

Gartner hype cycle (see Figure 2) for 3D printing presents the maturity and potentiality of certain technology. It explains the evolution of 3D printing technologies in five stages and gives an insight about the business potential of the technology. It helps companies to build their investment strategies and reduce risks in investments [9]. The hype cycle shows "consumer printing" to be passed the peak of expectations and is beginning to stabilize itself as one of the normal innovations in society [8]. Gartner hype cycle (see Figure 2) presents the basic polymer printing technologies to be already common and proved technologies in AM sector (such as material extrusion and stereolithography which can be listed as a part of the consumer printing term). These technologies belong to the desktop size printer category (see Figure 1) and therefore Gartner hype cycle proves that these technologies are suitable for educational purposes also.

The division between printer types (see Figure 1) form the starting point when planning AM education in this study especially from the user and application point of view. Even though the division may be steep, it helps to target the topics and issues in this paper through desktop size printers and their importance in AM education.

There are still a lot of differences, especially in integration and in functions between these two divisions (see Figure 1) (e.g. in educational environments containing machines from both categories) but these two are the main categories currently in AM. The same division can be seen in the terminology; the term "additive manufacturing" is used when discussing industrial applications and the term "3D printing" is used when the consumer point of view is discussed even though they mean the same thing. 3D printing is starting to be the regular term when discussing the technology [10]. For example, 3D printing is more commonly used term in engineering education especially in the name of the courses but when teaching the theoretical basis, additive manufacturing and other standardized terms are used. 3D printing term reaches more people and especially the students who are at the beginning of learning AM.

## 2 Literature Review

The topics presented in this literature study present the connected literature in the light of different applications in 3D printing that are used in education. The connection between AM education and industry and companies is important since it is the key component in planning AM education based according to work life demands. This review presents the challenges in AM education which present the identified problem statement in this study; a comprehensive pedagogical model is needed to develop AM education in engineering.

### 2.1 Applications of 3D printing

3D printing as a technology has rooted itself to the society and media; quite many people assume themselves to be 3D printing experts when they have seen or used such a device; usually only one type of machine has been used [11]. This seems to be sometimes the general assumption but in spite of this, 3D printing has its applications and experts who are using the technologies in far more advanced situations, which is the reality of AM. To understand better the different applications and the implementation of them in education, a detailed categorization of the applications must be created. This categorization can be presented through three main applications as seen in Figure 3 [1], [10], [12].

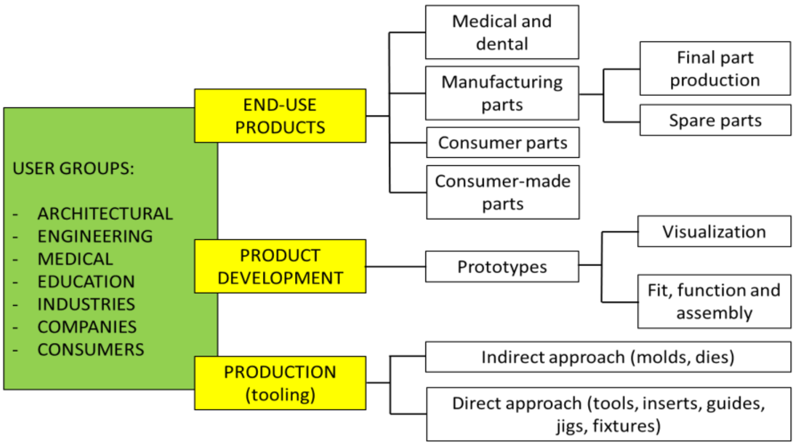


**Fig. 3.** Categories of AM applications and the possibilities to use them e.g. in education [1], [10], [12]

Figure 3 shows how the main user groups can be divided into the industry, companies, educational sector, research and to people, who use it e.g. for their own purposes or as a hobby. The figure can be used in education since the examples of the applications can be used directly e.g. as activities in 3D printing courses. These user groups include several different areas where 3D printing brings extra value or is sometimes the only reasonable solution to achieving desired educational goals.

Dividing the AM applications into different categories (see Figure 3) can be done in different ways and there is no standard for the presentation. This model is meant to be universal for many of the user areas of additive manufacturing. Different sources use categories such as prototyping, visual aids, final part production, just a few to mention. For example, for learning assignments with a certain goal, the categories offer a good way to target the assignment to certain area of engineering. In this study the applications of AM have been divided into three main categories (see Figure 3), which represent the most common way to define the usage of AM in different sources [1], [10], [12]. When developing AM education, these three categories serve as a starting point e.g. in drafting the learning objectives for courses from AM knowledge point-of-view. The main categories of different AM applications (see Figure 3) are end use products, product development and production (tooling).

*End use products* (see Figure 3) was the continuation from the original idea of rapid prototyping. As the technology developed in the 2000s, the machines were capable of produce products and components that were suitable directly to a selected application (so called direct manufacturing). This was especially one start point for the term additive manufacturing instead of rapid prototyping, which was the previous used term [1]. Many of the fabrication types, such as functional parts and spare parts, fall into this category. For example, one main point to learn manufacturing methods is to produce objects that can directly be used in desired application. By investigating and implementing this possibility with 3D printing, the students will learn that AM is one considerable manufacturing method among the traditional ones such as turning and milling.

*Product development* (see Figure 3) is probably the best-known application for the technology. 3D printing brings extra value to the design process by offering more possibilities in creating complex geometries and keeping the design work versatile [13]. This includes making visual hand-held versions of the design instead of 3D CAD models to help the designers and users to visualize the product better [1]. For example, product development is one of the main areas in Lapland UAS mechanical engineering education is and 3D printing offers flexible, affordable and logistically easy way to visualize the products and e.g. make prototypes for testing and viewing the product features.

*Production (tooling)* (see Figure 3) offers the possibility to produce tools and tooling aids for production. Molds and dies are used when casting or injecting products and different inserts, fixtures and jigs ease the manufacturing process when producing even-quality products [10], [12]. For example, when learning casting methods, 3D printing offers the possibility to learn tool production without the need for manufacturing them with traditional methods. This improves e.g. the understanding and learning of production planning.

### 2.2 Impact on companies and industry through education

3D printing has become a trend word and it can be noticed in everyday life and even in daily talks. 3D printing has rooted itself to the daily life since it has increased its visibility in the media, especially through its increased possibilities in the manufacturing area [14]. This sets demands and expectations for engineering education. For example, courses in engineering education are expected to contain 3D printing as default. Depending on the degree of education, the demands for the technology (e.g. equipment types) come from the required level of AM knowledge. Engineering education have to keep up with the demands from work-life representatives who are using AM in their functions and employ graduated engineers.

As the standardization of AM is progressing, some parts of the AM process can be validated but still the heterogeneity of printed parts and production time limitations present challenges for raising AM to the same level with the traditional manufacturing methods [15]. This means for education that AM must be researched in order to increase knowledge about AM and to decrease the gap between AM and the traditional methods. This is important since the graduated engineers export the information to the work-life.

The direction is correct; the manufacturing sector is becoming more and more aware of the possibilities of the technology since AM is used in many sectors such as industrial, medical and military, just a few to mention [10]. This means that AM must be implemented e.g. in engineering education firmly to the engineering curricula in order to fulfil the demands of the manufacturing sector. One key issue to address is how to ensure that AM knowledge reaches the manufacturing industry in a way which helps them to solve these challenges in adopting AM into the production processes. In Lapland UAS, the AM knowledge reaches the manufacturing industry through graduated students, R&D-functions and through separate continuing education courses planned to be held for work-life representatives in the future. However, this study concentrates in implementing AM in Lapland UAS mechanical engineering studies and R&D-functions, continuing education issues are not discussed here.

According to the experience of the main author as an educator, one important key factor enabling this is the principle of knowledge transfer, which is illustrated in Figure 4 [6], [16], [17]. This is based on the long collaboration between the main author's university (Lapland UAS) and the industry around the university's area (mainly paper, pulp and steel industry). This collaboration covers research projects, BSc theses and student employment (during the studies as internships and after the graduation) to the industry, just a few to mention. The dialog between the university and industry gives valuable feedback about the engineering education provided in the university.

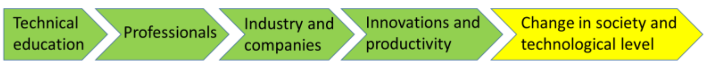


**Fig. 4.** Knowledge transfer principle [6], [16], [17]

Figure 4 presents the idea of knowledge transfer, which shows the path from technical education to the required target (in this case the companies and manufacturing industry). As mentioned in this study before, the main function of universities of applied sciences is to produce professionals and experts to industry and companies, who possess the latest information about modern manufacturing technologies, for instance [6]. For example, the information provided for the students must reply to the requirements of companies and manufacturing industry in order to strengthen the collaboration.

According to the experience of the authors, the requirements from companies and industry usually derive from the need for innovations and improvement in the operation of the enterprises. Their relationship to universities is based on collaboration. Companies and industry can benefit through common projects based on a need, for instance to develop something, which is one of the most common ways to do collaboration. This means that the curriculum in engineering education must be capable of intake topics from collaboration partners and enable students to function in work-life projects.

If this is looked e.g. from knowledge point of view, the information produced in engineering education is not always easy to adapt to the demands of companies and industry. Reason for this is usually the professional link missing between the education and work-life; the collaboration requires active people who work in the interface. If the teaching personnel is not involved e.g. with R&D projects, the low level of contact to work-life may complicate the adaptation of information. One way to solve this is to ask project work topics directly from the companies and industry and use contacts the personnel have.

Therefore, the employment of educated professionals is an important key factor in transferring the knowledge [16]. The role of the universities is to support and contribute to the development of innovations and sustainable economics in enterprises. As the companies and industry employ the educated professionals, it leads to new innovations in the companies and industry since universities can be seen the producers of the required knowledge [16], [17]. This sets demands and pressure e.g. to engineering education since the content of the learning must be modern and meet the requirements from work-life. The UAS sector must apply the modern practical methods in the learning and the didactical methods must bend to these. Based on the experience of the main author, this ultimately leads to positive change in society as viability increases through economic growth and technology advances through the knowledge transfer in companies and industry.

### 2.3 3D printing and engineering education – Challenges and possibilities

The growth of 3D printing has been enormous since the popularity of desktop size 3D printing is increasing all the time due to its relatively low price and easy accessibility (e.g. material extrusion technology). Desktop size 3D printing is closing the gap between industrial type printing from quality and machine reliability point of view. This has boosted the usage of AM in the educational sector since these factors facilitate the acquisition of AM to different purposes [1], [10]. Looking from educational perspective, this benefits e.g. the engineering education since now it is possible to acquire more sophisticated and accurate desktop size printers (e.g. vat photopolymerization and powder bed fusion of polymers) for teaching and learning.

In this study, the Lapland UAS mechanical engineering BSc level is used as an example. The need for developing the connection between 3D printing and engineering education derives from the 13 years' experience of the main author as an educator of engineers and from the collaboration with the industry of Lapland UAS area (paper, pulp and metal industry). The usage of 3D printing in the manufacturing industry in the area of Lapland in northern Finland is not yet very widely used (or partially at all). By connecting 3D printing to the Lapland UAS mechanical engineering education, it increases the awareness in Lapland area to utilize 3D printing in the manufacturing processes through knowledge transfer. Figure 5 (derived from Figure 4) presents the demands that the knowledge transfer model (see Figure 4) brings to engineering education.

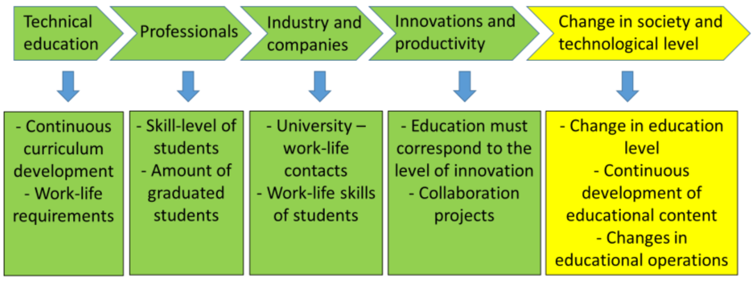


**Fig. 5.** Demands set to education by knowledge transfer factors. Modified from [6], [16], [17]

The arrangement of technical education (see Figure 5) requires continuous curriculum development in order to keep up with technical evolution. The requirements from work-life must be met through curriculum in different courses and learning events. The knowledge is transferred through educated professionals and therefore graduated students must possess required skill and knowledge level. The university must be able to produce sufficient amount of these skilled graduates every year. When finding employment in companies and industry, the university's work-life contacts are important and the students must possess required work-life skills learnt during studies (usually in practical internship periods). As the graduated students are working in companies, they produce innovations and participate to the increasement of productivity. This means that during the education they should learn to make innovations and know the meaning of productivity (hence the studies related to business and economics are important). Ultimately, the change in society and technological level means that the education must change in order to keep up with the social and technological evolution.

If the industry or companies do not recognize the AM possibilities, one function of universities is to encourage them to use AM. The collaboration between the university and industry / companies is the most active in internship possibilities in companies, BSc these processes, common development projects and in continuing education [18]. This indicates that the foundation of engineering education is vital and by including AM in the educational core, the knowledge transfer possibilities of AM will increase.

Based on the main author's observations, the manufacturing experts who have had their professional education 10-30 years ago, the studies did not include AM. This indicates that the future experts possessing necessary skills, need a curriculum that takes the principles of additive manufacturing (also in practice) into account at many levels of qualification, especially in under- and postgraduate level [19]. Based on the observations of the main author, the education of engineers in northern Finland has always leaned more to the requirements of the industry based on the features of the manufacturing processes. Therefore, one function of the Lapland UAS mechanical engineering degree is to increase the AM knowledge in the area although the traditional bulk product manufacturing industry the main focus. Bulk products consist of stainless-steel strip, paper and packaging products such as cardboard. There are several companies, which perform e.g. product development, who could benefit from AM in northern Finland. According to the main author's experience, there are also many companies who function as a subcontractor to the industry so by implementing AM into the engineering education, the possibilities and benefits of AM can be detected in the subcontracting companies. This can be seen in Lapland UAS from the lack of AM topics which could be used in student projects. The engineering education should encourage companies to use AM through common projects (e.g. through prototype production for some part that need to be designed). This way the knowledge about AM would increase in Lapland area of Finland.

When looking at the recent development of additive manufacturing, especially the speed of it, the educational sector is facing a challenge adopting the AM knowledge to the curricula [19]. According to the experience of the main author, the turnaround of a curriculum takes four to six years (under-graduate / post-graduate level) and during this time, the technology (e.g. AM) might have developed greatly already. The adaption of curriculum development into the speed of technological development of AM presents a challenge. Some educational institutions have solved this by arranging continuing education in the form of part-time training or short courses [19]. These are very good methods to implement a modern view into practice and this way the education can be targeted to a specific group of users. According to the main author's experience, curriculum is usually tied to a certain timetable and the course contents are planned at least half a year or even one year beforehand. Therefore, the curriculum should be flexible and intake "last-minute" topics e.g. through free elective courses but also fix the topics to the mandatory courses concerning the most important modern technologies. This is the reason why the curriculum development must be inspected according to the desired technology (e.g. AM).

## 3 Results

### 3.1 Creating curriculum considering AM education

The implementation of AM into the engineering education can be approached by opening up the basic process of developing a curriculum in Lapland UAS. The main author has acted as the main responsible teacher (guiding a team of teachers and R&D personnel during the development work) in renewing Lapland UAS mechanical engineering curriculum in 2014 – 2017. As a result, Lapland UAS mechanical engineering degree started in 2017 with new curriculum. The previous curriculum leaned more to separate courses targeting in specialization areas together with basic studies. There was no specific plot implemented in the curriculum besides addressing the main areas of the degree such as engineering design or maintenance through specialization studies. The professional studies were divided into special areas and part of them were elective for students to choose from. A new structure for the curriculum was introduced to enhance the concentration to the skills of a student and knowledge-based learning as presented in Figure 6 [20].

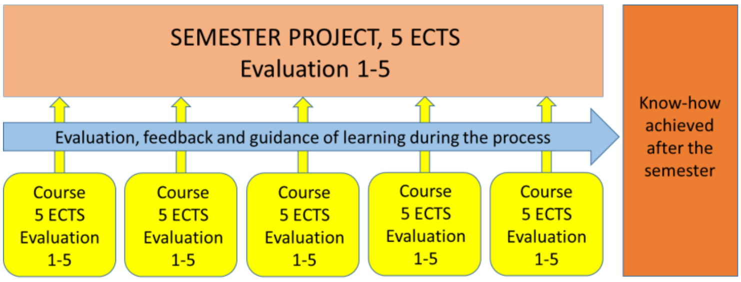


**Fig. 6.** Semester structure of the new curriculum [20]

Figure 6 presents the new curriculum dividing the four-year studies into eight semesters. In the center of each semester is a project, which collects the skills and knowledge acquired during the semester. The other courses during the semester work as supportive elements to the project offering information e.g. from mathematics, engineering design or other subjects. The know-how increases during the semester and the student achieves required skills after the semester [20].

The curriculum development followed Lapland UAS curriculum process which uses core content analysis in defining the central themes, contents and learning objectives. Core content analysis aims to define the themes, contents and learning objectives, which are derived from competences. Competences are partially pre-defined (general competences which are common e.g. for every mechanical engineering degree in Finland) and partially created to a specific degree. The process aims at balance the scope and requirements of the degree in relation to the pursued know-how [20]. During the curriculum planning work, the main author noticed that the process could also be used in implementing a certain technology into the curriculum since curriculum is the main tool for arranging engineering education. The curriculum model does not have to be generic (as it usually is) but a certain set of studies (e.g. AM) can be planned through the model by making it more accurate to match the AM technology as an example here. Through this, it is easier to notice where, when and how AM must be included in the process. This is one of the main observations of this study and it works as a background for the ***model of technical pedagogy*** developed in this study.

Even though the curriculum development process seems to be quite straightforward, it gives freedom to define the specific learning objectives and competences, which are included in the implementation plans of courses. After the startup of the new curriculum, an idea started to brew to implement AM more efficiently into the curriculum and to develop improved curriculum process for this purpose. In this study, AM presents the technology to be included in the curriculum.

The process of creating the curriculum can be divided into stages where certain actions are taken in order to produce necessary information. The basic structure of the process is presented in Figure 7 [20].

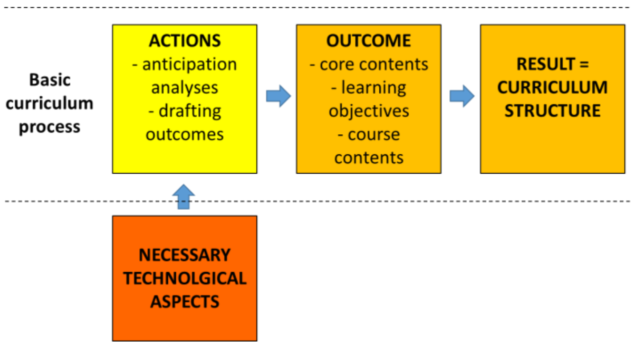


**Fig. 7.** Basic structure of the curriculum process with added technology. Modified from the Lapland UAS curriculum process [20]

The actions (e.g. core content analysis) (see Figure 7) are done in order to produce a certain outcome. The outcomes, such as learning objectives, work as the platform for creating the course contents. The technologies to be included (e.g. AM) are the ones that will be implemented to the curriculum. As an output (see Figure 7), the result presents the final structure for the curriculum containing the courses, timing of the courses during the semesters etc.

The basic curriculum process (see Figure 7) is used in implementing AM to Lapland UAS mechanical engineering degree. The following Figure 8 presents a detailed model of the curriculum process (see Figure 7), which includes the AM perspective. The model structure comes from the Lapland UAS curriculum process model [20].

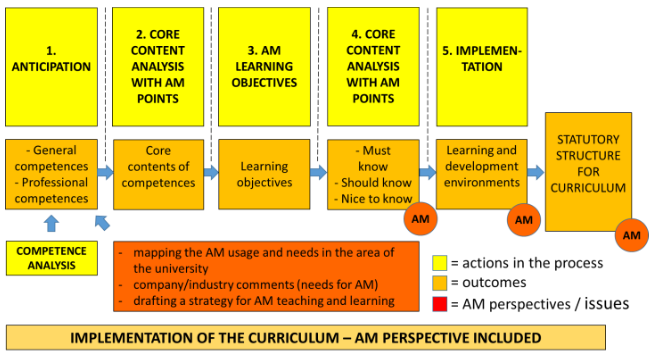

**Fig. 8.** Curriculum process with AM perspective. Modified from the Lapland UAS curriculum process [20]

Figure 8 shows the modified Lapland UAS curriculum process where the AM perspective has been included. The model shows where and how AM perspective must be included in the planning work. AM is the technological key point here since when designing a "technological" curriculum, skills and different perspectives are required in order to produce engineers who are capable of creative and versatile problem solving [21]. The following presents the description of the curriculum process first without AM perspective:

1. *Anticipation* (see Figure 8). The process starts from general competences, which are recommendations from the NQF in Finland (National Qualifications Framework). These include factors such as learning skills, ethics and international expertise [22]. Professional competences come from the demands of the industry and companies but also from the experience and results from previous curricula. These competences are meant to describe factors needed to perform certain work tasks such as potential, ability and qualification [20]. One important factor in planning the professional competences is to include the views of the industry and companies, which represent the "customer" in the process [20]. This happens by making a questionnaire to several partners from work-life and asking, what kind of skills and learning objectives are needed and expected in their operations.
2. *Core content analysis, learning objectives* (see Figure 8). The competences are analyzed and formed into core contents; this stage transforms the competences into learning objectives [20]. For example, in Lapland UAS mechanical engineering degree learning objectives such as the "ability to do mechanical measurements" or "understanding the failure mechanism of a certain machine" presents the skills the students will achieve during their studies.
3. *Core content analysis* (see Figure 8). These learning objectives are analyzed and categorized into three in the second core content analysis according to their importance; must know, should know and nice to know (e.g. must know: the student will know the basic rules of tolerances in technical drawings). These learning objectives are integrated into the course implementation plans, which act as a manuscript for arranging the course [20]. This stage forms an order of importance to the skills and helps to arrange the teaching for the subjects.
4. *Implementation* (see Figure 8). The implementation of these learning objectives happens in different learning and development environments such as laboratories, project work situations or in student projects [20].

As an *output* (see Figure 8), the statutory structure of curriculum is created presenting the four-year content of studies and learning objectives [20]. The structure comes from the University of Applied Sciences law in Finland and Lapland UAS degree regulations including basic, professional and free-choice elective studies, practical training and thesis [20]. This way the graduates will have the required expertise based on the demands of the same field in which they will be working after the graduation. The type of the new curriculum is knowledge-based and it forms the foundation of organizing learning [6], [20]. Problem-based learning forms the core of the learning process where the issues, phenomena and problems from real-life situations (such as an assignment from certain company) are handled and solved [6].

This kind of curriculum process will be used for implementing required AM skills into learning in Lapland UAS. According to the main author's experience, this is an efficient and organized methods to arrange engineering education and it offers a good way to view the engineering from broad perspective. Especially one of the most important part, the feedback from the companies and industries, can be included in the implementation plans of courses through partner questionnaires and work-life projects during the four-year period. This enables the equivalency of the engineering education to work-life demands.

Besides the regular engineering skills, the AM perspective must be included in the curriculum when the knowledge from AM will be transferred to companies and industry. When implementing AM principles into a curriculum process (see Figure 8), the following key factors should be considered according to the curriculum stages:

1. Anticipation (see Figure 8). This includes the demands of the industry and companies regarding additive manufacturing. First, the AM usage should be mapped in the area of the university by mapping the companies that are using or planning to use AM in their functions. This requires active conversation with key partners from work-life through e.g. BSc theses, common projects or R&D operations. A separate, targeted questionnaire can be sent to selected work-life representatives if there is no information available about the AM requirements and usage of the partners. The university should develop a strategy for implementing AM into their curricula; what the goals are for AM teaching and learning in the long run, what AM technologies are used, what skills must be acquired, what kind of collaboration could be done with the companies etc. When analyzing the competences, the companies should be taken with to the review process so that they can give comments. From an educational point of view, the quality of the education can be ensured this way since the competences can be targeted more detailed. This can be seen in education as increased connection to work-life topics.
2. Core content analysis, learning objectives (see Figure 8). The core content descriptions should be created in a way that they could be implemented e.g. into laboratory courses and they would match the requirements from industry/companies. Especially, when the learning objectives are drafted into sentences describing the learning objectives, they should include the required AM technologies as well as materials. The objectives such as "the student knows the principles of AM technologies" and "the student is capable of working independently with material extrusion technology" are the same descriptions for learning outcomes and work-life demands.
3. Core content analysis (see Figure 8). These AM skills and learning objectives drafted in stage 2-3 are analyzed and put into order according to their importance. The importance is defined from the basis of the demands (e.g. comments from work life) and according to the AM strategy of the university.
4. Implementation (see Figure 8). Functional curriculum needs modern AM environment; the equipment must meet the demands set by the competences. If a company

already uses a certain AM technology, it should be addressed in the learning situations of the topic. This can present a challenge to the education since the industry and companies use usually industrial style AM machines which can be too expensive to be acquired for the school. Therefore, the desktop size and reasonably priced alternatives are important. The work done in the AM environment should match the knowledge-based foundation of the curriculum; this can be achieved by having assignment topics from the work-life. If the learning requires more advanced equipment, one way to solve the problem is to arrange projects or collaboration with companies or other universities with industrial-type printers. The students could then work with equipment that is more advanced and the company and university would receive results through student work.

As an *output* (see Figure 8), the curriculum is constructed containing the courses and their timing within semesters. The placement of the courses and AM information must be planned carefully since the AM knowledge must grow during the four-year curriculum and cut through the required areas of mechanical engineering. This way the curriculum produces study content from AM, possibilities for practical training in AM learning environments and free-choice electives concerning AM. It can also act as a substrate for BSc theses producing research and development topics from AM.

### 3.2 The learning of AM in engineering

This type of curriculum structure (see Figure 6) fits very well for AM education purposes since the learning of AM consists of a theoretical basis and practical work. Practical part of the learning happens in laboratories (e.g. in laboratory courses) and learning environments with the AM machines [23]. For example, this enables the planning of semesters that are more targeted to AM through the curriculum. When a project (see Figure 6) is in the center of the semester, the project topic can contain AM perspective. The courses during the semester (including AM) support the realization of the project. This way the whole semester can be AM oriented.

According to the main author's experience, the production of 3D printed part is relatively easy at its best but the AM still has a lot of challenges such as the versatility of 3D printer software, unexpected problems in the printing process and the lack of standard for the safety of 3D printing (e.g. particle emissions, material handling). In different 3D printing courses held in Lapland UAS, the process of learning has usually followed the same kind of path, which derives from facing challenges in the actual printing process along with the theory connected with the subject (e.g. finding out the reason for nozzle collision to the part during material extrusion). Based on the experience from the courses, usual reason is the insufficient adhesion of the first layer with the printing platform causing the separation of the print from the platform. This leads to the nozzle collision with the part and to the print failure.

This happens usually in the beginning of the learning process, where the amount of problems is inversely proportional to the experience with the printers. Without sufficient experience from the common problems and failures, the student is the most likely to face them in the beginning without the ability to prevent them before they happen (e.g. with correct design or machine settings).

According to the main author's experience, 3D printing is a technology which cannot be learned through plain theory. Therefore, problem-based approach is an efficient way to learn AM. This principle of comparing the amount of problems with the user's experience can be seen in Figure 9.

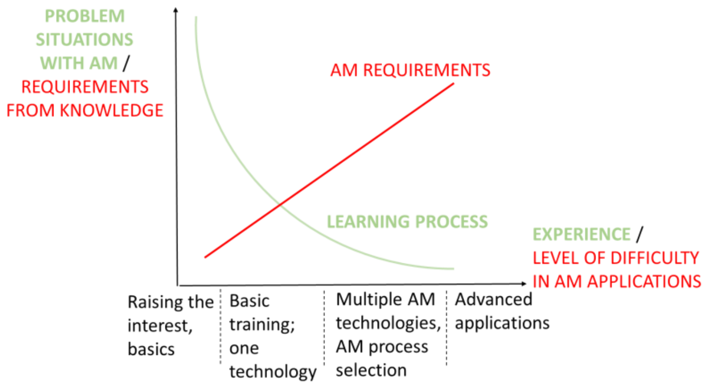


**Fig. 9.** Inversely proportional learning of AM

Figure 9 presents the idea concerning AM learning and its requirements. The lighter green curve presents the inverse learning process; due to the lack of knowledge and experience, problems appear more easily in the beginning. This is a result from the student's understanding about his/her own problem-solving skills and from the amount of education related to the problem-solving skills [24]. Therefore, successful adoption of new technology requires education from the area. Education usually starts from the theoretical aspects but learning by doing has presented to be an important part in supporting the education. As the experience develops, the user is capable of handling the more difficult situations independently. According to the experience of the main author, the darker red line (see Figure 9), is used to describe the requirements that users face from AM technology. The line is steep since the further the students proceeds in learning certain AM technology, the more experience and knowledge it requires.

According to the experience of the main author, based on 3D printing courses held for Lapland UAS mechanical engineering students, the AM requirements in the learning process can be described at four levels (see Figure 9): 1) *raising the interest*, 2) *basic training*, 3) *multiple AM technologies* and 4) *advanced applications*.

*At the first level* (see Figure 9), requirements from AM technology point of view are low (e.g. introducing material extrusion printing is rather simple) but as the situations progress into more advanced situations (e.g. more complex situations in the printing process with the powder bed fusion of polymers), the requirement level rises. The learning should be based on simpler things at the beginning of the process; this stage is meant to raise the interest and familiarize the user with the technology. This includes the introduction of the technologies and design principles, showing different cases from AM technologies. This lays the ground for the AM learning and raises the motivation to learn.

*The second level* (see Figure 9) introduces the user into the practical work. One good way is to do this through material extrusion technology since the threshold using it is lower than with the other technologies. This is usually the point where most of the regular users are; they use material extrusion in producing printed parts and at the same time the knowledge increases about the design principles and technology. This is the point where many educational units stay in their AM education and it is completely reasonable and accepted since using material extrusion offers many advantages with relatively low usage and maintaining costs. This level can be taken forward with just one technology but at some point, the limitations of one technology become an obstacle and prevent the student in progressing concerning the AM spectrum.

*The third level* (see Figure 9) is where several AM technologies are introduced (e.g. material extrusion, vat photopolymerization and powder bed fusion of polymers). The students have to reflect the product idea on the actual usage purpose and think (through AM process selection methods), which AM technology is the most reasonable to be used in this situation. This is the threshold that separates the regular users from advanced/expert users since using multiple technologies enables the possibility to define specific product features (e.g. material properties, accuracy, surface finish and usability).

*The final fourth level* (see Figure 9) is the advanced level; the student can work independently with multiple technologies and learn new AM technologies. The learning threshold is lower in this stage (the student possesses sufficient experience already from AM in order to learn new technologies more easily). This leads into advanced AM applications, where the possibilities of AM can be fully used and understood. This level is so called the industrial level, which has to be achieved in order to produce experts for the industry and companies.

Based on the experience of the main author, this model (see Figure 9) help in identifying the phases of the AM learning process and to create AM strategy through identifying the desired target level of expertise for the education.

### 3.3 Creating the technical pedagogy model

The term technical education is the de facto term usually used when discussing educating professionals and producing knowledge to different technical areas, especially when viewing the education of engineers [25]. It covers most of the technical areas but does not offer a clear solution for the pedagogy of certain technical area. This is because every university uses their own curriculum and methods in arranging the education. Most of the professional competences are not standardized in Finland in the University of Applied Sciences sector. This reflects on the main author's experience in educating mechanical engineers; the traditional pedagogical education of teachers offers good tools for arranging the learning process but is does not handle the technical details. Usually, the details are left for the teacher to apply in the best possible way according to the curriculum of the degree.

When looking at the education of engineers more detailed, the term engineering pedagogy define the pedagogical arrangement of educating engineers. It operates in the interface between the technical side of engineering and traditional pedagogy and education [26]. This offers a detailed way to view the technical education but more accurate model is required when learning a certain technology (e.g. arranging AM education). This shows the gap in the current literature since teaching technical and detailed subject such as AM, there is a need for this kind of pedagogical model.

In order to identify the construction of AM based education and curriculum, a description of more targeted pedagogy must be created. This derives from the main author's experience in curriculum development and from the gap in the current literature. The implementation of curriculum with AM perspective (see Figure 8) form the foundation for the structure of engineering education and gives the core content to courses [20]. For the actual implementation of AM education in different courses and learning events, teachers and educators need more detailed model for arranging AM education from a pedagogical point of view. A starting point for identifying the factors for the model can be seen in Figure 10.

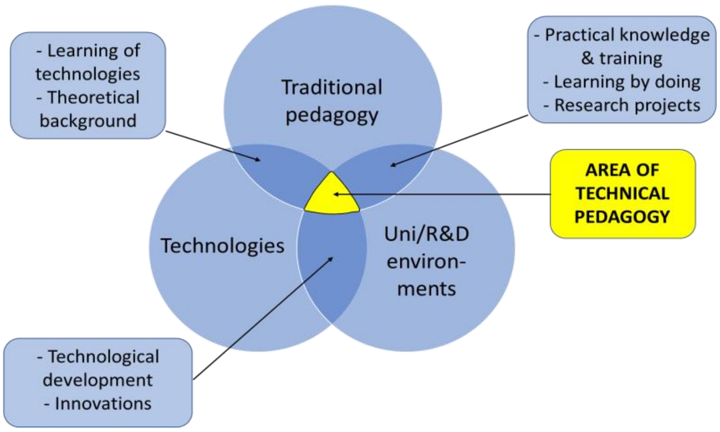


**Fig. 10.** Factors for the model

Figure 10 presents three foundations for the model; traditional pedagogy, technologies and university and its R&D environments. Traditional pedagogy is included in the professional teacher skills needed through the proper pedagogical education of a professional teacher. Technologies (e.g. additive manufacturing) present the topics that need to be learnt and integrated into the learning process. This includes the usual technological development (learning of the new technologies) and different innovations. University and R&D environments present different places (e.g. laboratories and learning environments) where practical learning can take place. The overlapping areas (see Figure 10) between the three foundations presents the functions which the overlapping enables. Pedagogy and technologies enable the learning of the necessary theoretical background for the desired technology. Pedagogy and environments enable the practical learning, especially through learning by doing. This can also be a substrate for research projects when the university R&D-functions are involved. Technologies and environments enable the development of the technologies. This shows that the learning process can also lead to new innovations. In the middle of all is the birthplace for the idea and model of technical pedagogy (see Figure 10). It combines the three foundations and the overlapping areas by giving the space for new kind of teaching and learning model. According to the experience of the author, by recognizing the so-called building blocks for any pedagogical model, it helps to orientate the planning to right direction. In this case, these three factors are the most important starting points.

By identifying the factors behind engineering education, pedagogy and the crossing point between the factors (see Figure 10), the ***model of technical pedagogy*** is created with AM as the target technology. Figure 11 presents the structure of technical pedagogy with AM perspective.

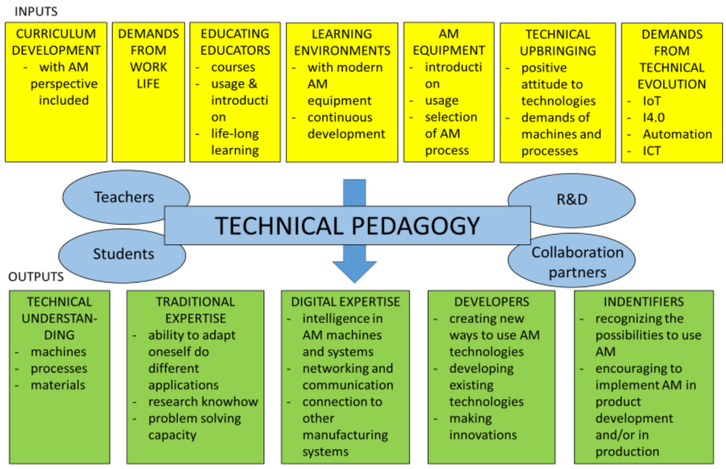


**Fig. 11.** The model of technical pedagogy

Figure 11 presents a model for arranging technical education in different areas concerning certain technology, in this case AM. The model:

- Consider necessary factors for implementation the teaching of AM
- Helps to draft the strategy for arranging the education of the technology
- Works as a checklist for planning the actual implementation (e.g. course)

It offers a platform for understanding what technical education requires and it can be applied to different areas of engineering technologies.

The ***model of technical pedagogy*** (see Figure 11) is based on the relationship of inputs and outputs which are the factors the education requires in order to produce a desired result. In this case, the advanced AM education is the target. The inputs (see Figure 11) are the factors that need to be arranged when planning to teach and learn certain modern technology such as AM. The inputs (see Figure 11) combine the curriculum work and competences to the learning environment arrangement and they include the need for arranging education and training to the educators (teachers). This includes the demands from work life (through curriculum work and work-life connections). The modern aspect of technological evolution especially from the smart manufacturing perspective is also included through industry 4.0 [27]. This is connected to the on current Lapland UAS digital laboratory environment which concentrates on smart manufacturing systems. Technical evolution (see Figure 11) factors in the model work as enablers in giving the possibility to include them in the education. Based on the experience of the main author, this description of the technical pedagogy must contain the upbringing aspect. The educational provider must enable a positive atmosphere towards the subject at hand. By creating a learning environment or event that motivates the student to use technology in the studies, it will boost their level of technical skills.

In the middle of the model (see Figure 11) are the operators. The operators are the students, teachers, the R&D department of universities and collaboration partners, who function within the model. Collaboration partners are e.g. work-life employers, research partners or certain technology collaborators (such as AM equipment manufacturers). These operators enable the model (see Figure 11); teachers and R&D department function mainly as the *builders* of the infrastructure for the inputs. The students are the *target group* for this model, collaboration partners function on both sides; they partially enable the *substrate* for the inputs but are also the *customers* since graduating students take their expertise from the technology to companies and industry.

The outputs (see Figure 11) are the factors need to be considered when arranging the education. The outputs present the desired competences and targeted learning objectives which can be integrated into the implementation of AM courses. When these are in order, the model produces solutions to introduce new technology to students. These solutions (outputs) help to identify the desired learning objectives in broader perspective than just as learning objectives in individual courses. By using this model, the educators and institutions can:

- Implement desired technical subjects into the engineering curriculum (model work as a checklist for planning the education)
- Understand what is required to implement technical subject to engineering through traditional pedagogy (inputs)
- Understand what is required to arrange the practical learning situation (e.g. courses, laboratories) (outputs)
- Create technology-based competences and learning objectives (outputs)
- Find out solutions to be used in introducing new technologies to students (outputs)
- List all the operators that work within the model

Technical pedagogy is an important tool especially for engineering education since it can be used to keep the education up to date according to the general technical development. The development of education through a traditional curriculum process does not always consider the details in certain technology. For example, [28] emphasizes the importance of curriculum development to reach the required quality of traditional engineering education set by the needs of work-life and industry. With this model, the technical details can be considered and implemented, especially when drafting the competences and learning objectives in curriculum work.

## 4 Conclusion

Implementing engineering education has always leaned to the usage curriculum, learning objectives and competences. This has been the main guideline always since curriculum offers some kind of standard how to produce experts in their own field. 3D printing has already shaken the manufacturing and educational sectors with the versatility of the technology and fast development pace. The sectors are now detecting the real possibilities of the AM technology. Narrowing the gap between the technological development and education is the most important when knowledge about AM is transferred to industry and companies. The change is already happening but it must be ensured that the quality of the knowledge is sufficient and better targeted to certain areas of the society (e.g. certain manufacturing sector).

Creating and updating curriculum, competences and learning objectives are the most important task to be done when the AM knowledge is transferred to work-life from engineering education. When planning and updating a curriculum, the basic curriculum process can be used for including certain technology in it through implementing the features of the technology to the planning process stages properly. ***The curriculum process with AM perspective*** presented in this study can be used in in implementing AM into any engineering education since it offers a clear process model for the curriculum work. This helps the educators in their curriculum development work when technical aspects (e.g. AM) are implemented into the curriculum.

In order to implement the learning of AM in practice, the nature of the learning must be understood. ***The inversely proportional learning path of AM*** presented in this study show how to arrange AM courses taking the nature of AM requirements into consideration with respective to the learning process of a student. This presentation of AM learning helps the educators to plan the pedagogical path in AM courses in order to achieve efficient learning for the engineering student.

***The model of technical pedagogy*** presented in this study shows a tool for bringing the traditional curriculum work and the introduction of new technologies together. The model brings the three most common factors of engineering education (traditional pedagogy, technologies and the environments of the university and its R&D operations) together. Educators can use the model as a checklist when planning the education of technical subject, such as AM. This model helps to develop a strategy implementing AM into the technical education program by showing which factors must be considered in the implementation stage of the education. The results of this study can be used in planning engineering education, especially through curriculum development with specific technology such as AM.

3D printing can be seen as the next industrial revolution but it must also be seen as a reformer of technical education. This requires the change of attitudes, investing in modern learning environments with several AM technologies and the motivation to change curricula.

## 5 Acknowledgement

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# Publication III

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# THE DESIGN PROCESS OF AN OCCUPATIONALLY SAFE AND FUNCTIONAL 3D PRINTING LEARNING ENVIRONMENT FOR ENGINEERING EDUCATION

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**Abstract:**
Learning environment is a physical environment which enables and supports interaction and learning of an individual. Practical learning happens usually in a physical learning environment allowing students to learn through using a certain technology when engineering education is in focus. 3D printing offers a low-cost and easy to access way to learn technology through different 3D printing technologies. There is lack of proper guidelines and solutions how to design practical and safe 3D printing learning environment in current literature. The design of a 3D printing environment consists of designing the physical environment and the operational model for the environment. The most important issue in the design work is the occupational safety of the environment including identifying different risks for health. This study presents a process of designing a 3D printing environment in Lapland University of Applied Sciences mechanical engineering degree programme (B.Sc. degree) including layout and operational planning from educational point of view. The study emphasizes the importance of connecting technology with learning in engineering. This study also includes an educational process model presenting the actions which the environment enables from educational point of view. Functionality of the environment refers to the possibility to learn by doing and work in the environment in a way that enables diverse learning possibilities. The process

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model presents how a 3D printing learning environment can be connected with other functions in a university or in a company and therefore be a part of a manufacturing chain from educational point of view.

**Keywords:** 3D printing, additive manufacturing, learning environment, laboratory, occupational safety

## 1. Introduction

The Finland Ministry of Justice defines learning environment to be an environment, which takes the needs of the individuals into account and supports interaction and learning. This happens by offering safe, calm and healthy circumstances for learning (FMoJ, 2012). Safety is referred as occupational safety in this study and it considers all the means to be used to minimize and remove the risks to health such as injuries, accidents and hazardous incidents (FMoJ, 2002). Learning can also be seen as an output of teaching when the know-how of an individual is being understood and developed. Learning environments are usually physical environments (in addition, the social and psychological aspects are involved) that have different dimensions. Learning happens when the individual interacts and forms his/her own concept from the learning environment (Savander-Ranne et al., 2013). Learning environments in engineering are usually technology-driven where students apply equipment to learn certain technical phenomenon or solve a problem. The future of learning emphasizes the learners´ own initiative in learning (Kinshuk et al., 2016). Environments, which enable students´ independent learning combining practise and learning are in focus when educating future experts. Learning environments should reflect on learners´ needs and give a response to the learning experience (Mikroyannidis et al., 2015). According to the experience of the main author, this means that learning environments in engineering education:

- should enable the independent work of a student,
- should visualize theoretical aspects in practical ways,
- should provide technology modern enough to allow student to be able to effect to the used process and
- the outcome from using certain technology should be clear enough for the student to be able to analyse the results and reflect them to own learning.

In this study, 3D printing is the technology in focus of learning environments in engineering education. The 3D printing environment of Lapland University of Applied Sciences (Lapland UAS) mechanical engineering degree programme in Finland will function as the platform to this study. The study is limited to BSc and MSc level in Higher Education Institutions (HEIs´). Additive manufacturing (AM), more commonly known as 3D printing is a technology where an object is manufactured from 3D CAD model through software-based modification and treatment of the model prior actual printing. In the actual manufacturing phase, the object is printed layer by layer with selected 3D printing technology (Gibson et al., 2015). 3D printing has rooted itself especially to the educational sector at many levels (from the junior level to universities) especially through low-cost, desktop applications (Haavi et al., 2018 and Wohlers, 2017). These enable the implementation of the technology to engineering education which is at focus in this study. Figure 1 presents the three most widely used 3D printing technologies worldwide which are polymer-based technologies.

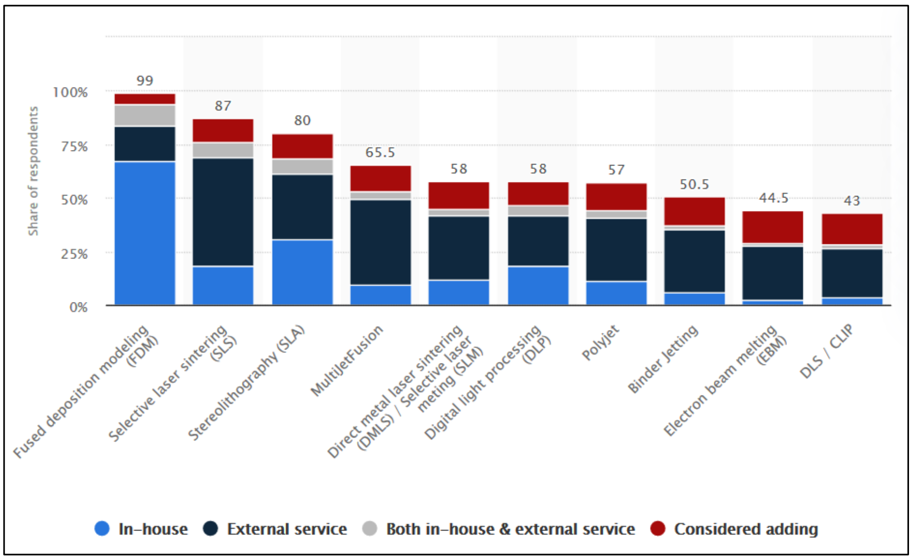



**Figure 1:** Most widely used 3D printing technologies worldwide in 2020 (Statista, 2020)

As seen in Figure 1, the three most used technologies in 2020, Fused deposition modelling (FDM), Stereolithography (SLA) and Selective laser sintering (SLS), are polymer printing technologies. These abbreviations are commercial terms while the standardized terms are according to SFS-EN ISO /ASTM (2017):

- FDM = material extrusion
- SLA = vat photopolymerization
- SLS = powder bed fusion (of polymers)

FDM is a technology where material is deposited in a molten state through a nozzle layer by layer according to the basic principle of additive manufacturing. Material is in filament form and can be of different polymer types, e.g. PLA, ABS, Nylon (Gibson et al. 2015 and Wohlers, 2017). The typical reachable dimensional tolerance of FDM is from ±0.2 to ±0.5 mm while the layer height is at minimal 0.1 mm which makes it an optimal for fast prototyping or even with its quite wide variety of applications, also to an end-use product purpose (Gibson et al., 2015, Wohlers, 2017, Garzon-Hernandez et al., 2020 and Mohamed et al., 2015).

SLA is a technology where photopolymer liquid resin is being cured with ultraviolet radiation (UV) layer by layer. As the radiation cures the resin, it solidifies in a chemical process called photopolymerization. The used radiation source is typically an UV-laser, which is directed to its target through laser optics and scanner. The used liquid resins are UV-curable photopolymers, usually epoxy-based with some amount of acrylate. The advantages of SLA technology are its quite high accuracy and the level of surface finish. With the minimum layer height of 0.025 mm and dimensional tolerance from ±0.05 mm to ±0.1 mm, this makes it an ideal technology for functional prototypes and especially small parts with better level of details due to the good dimensional accuracy compared with the other two technologies (FDM, SLS) (Gibson et al., 2015, Formlabs, 2019 and 3D Hubs, 2019).

SLS is a technology in where polymer powder is fused together with a laser layer by layer in a powder bed. The principle of the technology is similar than in the powder bed fusion of metals but instead of full melting, the polymer powder particles are being sintered together and forming a solid part. One important factor is that with a powder bed, separate support structures are not needed giving more freedom to the design. Used material is usually polyamide (nylon). With the minimum layer height of 0.075 mm and dimensional tolerance of ±0.3 mm makes it an ideal for the prototyping of functional assemblies and even to end-use products (Gibson et al., 2015, 3D Hubs, 2019 and Sinterit, 2019). These three most widely used AM technologies are in focus when discussing the design work of a 3D printing learning environment in this study.

## 2. Literature Review

The fast development and generalization of desktop 3D printing in different environments such as homes, offices, schools and libraries has given rise to occupational health risk due to the need for proper ventilation and handling of different chemicals. The growth of the technology has been faster than the research of the safety of 3D printing. The risks behind using 3D printing exist in the different stages of the printing process. Figure 2 presents the different 3D process stages including the risk of exposure to the emissions and chemicals (Unwin et al., 2013, Stockmann-Juvala et al., 2016 and FIoOH, 2016).

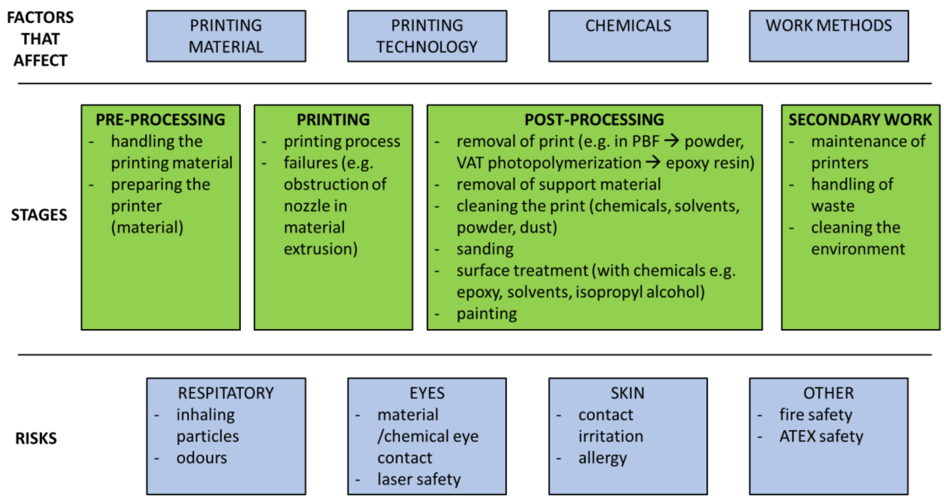



**Figure 2**: Different stages of 3D printing process including risks
(derived from Unwin et al., 2013, Stockmann-Juvala et al., 2016 and FIoOH, 2016)

As seen in Figure 2, there are four different factors affecting the risks through different stages of 3D printing work. The risks present the targets for hazard to health such as respiratory, eye or skin irritation and other risks such as working with flammable material (Unwin et al., 2013, Stockmann-Juvala et al., 2016 and FIoOH, 2016). The factors are printing material properties (chemical and physical composition), printing technology (the features of the technology), chemicals (used in different stages) and work methods (user-based). For example, comparing material in filament form with liquid resin, liquid resin presents a greater hazard and risk for health due to the nature of handling the material. The work methods have also an effect to this. If the user does not follow proper safety instructions, the risk for hazard increases. The stages present four possible phases where the risks can occur. The stages are pre-processing, printing, post-processing and secondary work. For example, loading the printing material in SLS can be a risk due to possible powder exposure if proper safety equipment is not used (safety masks and clothes). Post-processing e.g. handling IPA alcohol in the SLA print washing stage presents a risk. Out of this, two main issues can be noticed: exposure to emissions during printing and during working with the printing materials and chemicals that are hazardous to health. This presents a growing demand for safety solutions (especially practical ventilation and air extraction solutions) for 3D printing, especially during exposure to long printing times (Zontek et al., 2016 and Viitanen et al., 2016). 3D printing of polymers happens by melting, fusing or curing thermoplastic or thermosetting material in target temperature. This releases different sized particles causing especially a respiratory hazard. E.g. PLA or ABS produce emissions such as gases, particles and odours at their melting temperature range 180-280°C (Viitanen et al., 2016 and Unwin et al., 2013). The only measure to be taken, which is proved to be sure to control the emissions, is to build completely closed casing to open desktop printers. Printers with their own casing and air removal/filtering system still require air extraction due to residue particle emission and odours (e.g. common EPA-filters filter up to 95% from the particles). Leading the emissions from the casing outside from the 3D printing event is vital for controlling the emissions (Stockmann-Juvala et al., 2016). This study presents an example for controlling the emissions through casing and separate air removal system.

Finnish Institute of Occupational Health (2016) released a research about the gas and particle emissions at the different work stages of 3D printing. In the research, the emissions of 3D printing in small and industrial scale with PLA and ABS were investigated and measured. Research was done by simulating an office space (48m$^2$) with an air exchange rate of $\left(5-10\frac{\text{dm}^3}{\text{s}}\right)/\text{m}^2$. The guideline for office space air exchange rate was informed in the research to be $\left(1.5\frac{\text{dm}^3}{\text{s}}\right)/\text{m}^2$. The measurement and results are based on to the official OEL (Occupational exposure limit)-values that present the concentrations in the air known to be harmful for health. The main conclusions according to Stockmann-Juvala et al. (2016) inform that PLA and ABS filaments are the most widely used printing materials in Finland. This refers to the fact that FDM is the most widely used 3D printing technology in the world (as presented in Figure 1) (Statista, 2020). Research stated that open type and desktop size small-scale 3D printers are emitting nanoparticles (size < 0.1μm). Due to the nature of these three technologies, most widely used post-processing chemicals are alcohol or isopropyl alcohol and acetone. The research monitored especially the air exchange conditions in the space and it was noted that the allowed target level of emissions is reached with less than 2 hours of printing in the space. In long-term printing, the normal air exchange rate of the room is not sufficient (especially when using multiple printers) and therefore local air extraction is required. As a conclusion to this, protective measures (e.g. casing) are required if printing last more than two hours. The research also investigated separately the three most widely used 3D printing technologies. When using open-type desktop printers with FDM, local exhaust ventilation situated above the printer is not sufficient. It is difficult to reach the printing head due to the geometry of the printers, which is the main source for nanoparticle emissions. When using SLA with epoxy resin, handling the resin does not present particular respiratory exposure. Since epoxy causes allergic reaction and it is highly irritating material, the handling of the material must be performed with high caution and avoid direct skin contact. When using SLS, fusing the polymer particles raises the nanoparticle level in the room. In the handling of the print (e.g. cleaning excess powder from it) the level of particles is at the level of the normal room emissions (maximum) when ventilated cabinet is used (with air extraction or/and local air suction). As the research states as one of the main conclusions, the most efficient way to handle the emissions is to use **encased printing** (by building an airtight box around the printer with proper replacement air solution) with air extraction to outside from the printing environment. This keeps the nanoparticle emissions in allowed level. Chemical safety must be ensured in the space with proper measures considering the preservation of chemicals and occupational safety when handling the waste and the chemicals.

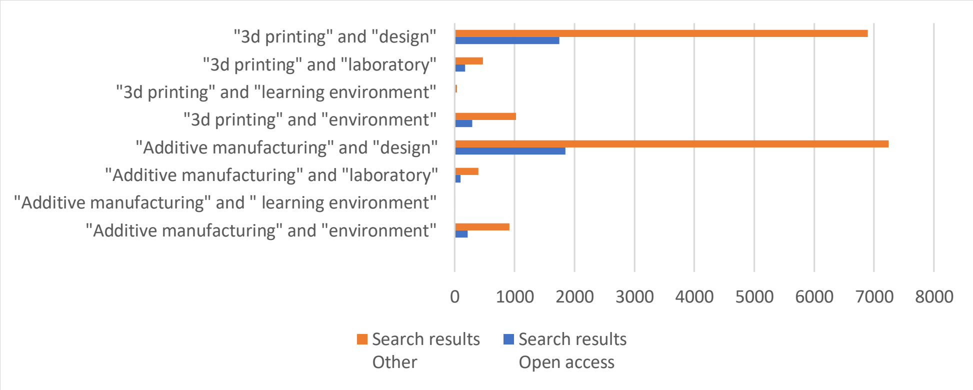
These authorised research results present a solid foundation to the design of a 3D printing environment presented in this study. The main conclusion from these to this study guiding the design of the laboratory state that every printer must be encased and equipped with air extraction to a separate air channel. If the printer is encased and has its own air handling equipment, the extraction air must still be removed to the separate air system. Handling of the powder material must be done in a separate cabinet with air extraction and personal safety mask must be used when handling the material. While the handling of the resin material in SLA, safety wear (protective gloves and jacket, a facial mask) must be used to avoid contact with skin and eyes. All the hazardous and flammable material must be stored in a ventilated fire-proof cabinet. This includes e.g. the cleaning cloths used in cleaning excess IPA from the print in SLA.

## 3. Objectives of the study

The aim and purpose of this study is to present a process for creating physical 3D printing learning environment in Lapland UAS mechanical engineering degree programme and present the importance of planning in the design phase from educational point of view. This study also presents a model for the operation in the environment which enables other educational units (and companies) to benefit from it in their own development work on similar environments. The model also shows how 3D printing can work as a part of the manufacturing chain. Current literature concerning 3D printing environments does not include clear instructions e.g. handling emissions during printing and therefore this study presents solutions to create functional and occupationally safe 3D printing learning environment. In this study the functionality of the environment refers to the possibility to learn by doing and work in the environment in a way that enables diverse learning possibilities. This study is limited to desktop level 3D printing of polymers due to the fact that the Lapland UAS 3D printing laboratory is at focus in this research. The laboratory is equipped with desktop level 3D printers with FDM, SLA and SLS, which present the 3D printing technologies used in the environment of this study. These are also the three most used 3D printing technology worldwide (Statista, 2020). Designing the safety of the environment is based on the recommendations of Finnish Institute of Occupational Health. This study concentrates only on polymer materials such as PLA (polylactic acid), ABS (acrylonitrile styrene acrylate), polyamide (nylon) and liquid resins.

A large variety of research papers considering the arrangement and learning of 3D printing in different educational units and environments can be found. These present solutions e.g. implementing 3D printing into curriculum, drafting learning tasks or methods or presenting more sophisticated results for analysing 3D printing learning outcomes. When searching information and research results from the arrangement and design of actual 3D printing environments and laboratories, only scattered and scarce information can be found. Table 1 presents search results (2020 – 2010) from SCOPUS database (Scopus Preview, 2020).

**Table 1**: SCOPUS (2010 – 2020) search result for related keywords (Scopus Preview, 2020)




As seen in Table 1, the keywords or their combinations connected with additive manufacturing, 3D printing, environment, learning environment, laboratory and design present the search results of number of research papers from the past ten years. The results have been divided into Open Access publications and to Other (e.g. fee required to view the research). According to results number of Open Access research from the topics is quite limited. By investigating the search results in detail, the following can be noted:

- "environment" refers mostly to environmental issues in 3D printing,
- "learning environment" refers mostly to functions and operations in certain 3D printing related environment or to learning factors in such environment,
- "laboratory" refers mostly to 3D printing work done in laboratory environment or to specific outputs from 3D printing work and
- "design" refers mostly to the design factors in AM process such as DfAM (Design for Additive manufacturing).

These search results give the indication from the current situation of actual research results from the implementation of 3D printing environments. This presents the need for this study in order to show a case study from the actual implementation of a 3D printing laboratory. This study can be used in other HEIs´ when planning a safe 3D printing laboratory.

## 4. Results and findings

The results of the research have been presented in the following sections and they have been divided according to the topics.

### 4.1 Background for the development of the laboratory

The department of mechanical engineering in Lapland UAS started a project in 2017 to develop new smart manufacturing laboratory environment called the "Smart Lab" project. The project was divided into two sections where the first part was funded by the

European Regional Development Fund (ERDF). This part targeted to the acquisition of modern digital manufacturing equipment. The second part was funded by the European Social Fund (ESF) and it was targeted to develop the education and expertise around the Smart Lab especially through integrating subjects from the project to the mechanical engineering degree studies. The project is divided into the following sections according to Figure 3 (LUoAS, 2017 and LUoAS, 2018).

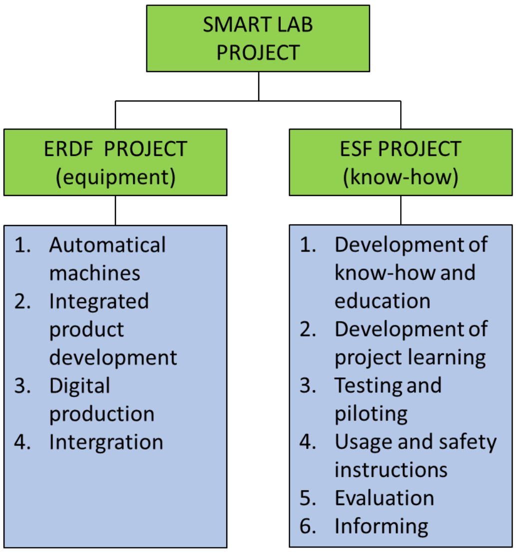



**Figure 3**: Description of the Smart Lab project (LUoAS, 2017 and LUoAS, 2018)

As seen in Figure 3, the ERDF part of the project concentrates on the acquisition of the equipment. The goals were divided into work packages according to LUoAS, 2017 and LUoAS, 2018:

1. Automatic machines: The development and building of a new intelligent laboratory for machine automation including pneumatics and hydraulics.
2. Integrated product development: The development of product development functions through CAD, 3D scanning, additive manufacturing (designing and building new 3D printing laboratory) and digital information transfer between product development and manufacturing.
3. Digital manufacturing: Development and building of a digital manufacturing system containing Industry 4.0 and IoT-elements in manufacturing and automation. The digital manufacturing system is able to fabricate automatically small assemblies with different parts. The work package includes also equipment with more traditional manufacturing processes such as sheet metal work and welding. This work package includes the acquisition of Enterprise Resource Planning (ERP-system) and Product data management (PDM-system). The latter

two connect the system with the product development functions in work package 2.

4. Integration: Combining the previous elements into one entity and connecting it with engineering education and to the research and development functions of Lapland UAS.

This study concentrates on the development of a new 3D printing laboratory and education as presented in work package 2 (integrated product development).

The ESF part of the project concentrates on developing and increasing the expertise and education about the Smart Lab topics in Lapland UAS and in the industries and companies of the area. The goals presented in Figure 3 are as follows:

1. Development of know-how and education: to increase and develop the competence of the Lapland UAS and industry/companies' personnel to meet the demands of digital manufacturing.
2. Development of the project learning; developing problem-based learning in projects to answer the needs of learning, research, development and innovation (RDI) functions and companies.
3. Testing and piloting: building and piloting new learning projects in the Lapland UAS mechanical engineering degree, the development of the education.
4. Usage and safety instructions: increasing and ensuring the quality of the operation in the project environments.
5. Evaluation: inspecting the results from different tasks such as new learning projects and developing them further through iteration.
6. Informing: spread the information about digital manufacturing to the industry, companies and students (LUoAS, 2017 and LUoAS, 2018).

The main goal of the ESF part of the project is the improvement of the quality of mechanical engineering education in Lapland UAS. Through this, it will benefit companies as there is available personnel with better knowledge and skills of digital manufacturing to be employed. The development of new operating models and technologies is highlighted in the project (LUoAS, 2017 and LUoAS, 2018). This study concentrates on especially to the development of the 3D printing education in Lapland UAS by offering a method in order to learn 3D printing more efficiently through several technologies and selecting the most suitable 3D printing technology through AM process selection model.

### 4.2 The design process of a 3D printing laboratory from education point of view

The development of the new Lapland UAS 3D printing laboratory started in 2018 when the experience from the previous 3D printing courses and projects was collected and the planning of the new functions was started. Lapland UAS has practised 3D printing from 2016 with FDM devices (small-scale printing). The previous 3D printing environment consisted of 6 FDM-printers in a temporary space of ~37m² for the printing work. The old environment was in operation from 2016 and it produced basic knowledge from 3D printing through different courses and student projects. The Smart Lab project enabled the planning of a completely new environment and the guidelines for planning were drafted according to existing research from the occupational safety of such environment and to acquired experience. The most important goal was to create an occupationally safe learning environment without zero particle emissions or odour (including chemical safety). The 3D printing laboratory integrates into the Smart Lab through ERP and PDM system (with the implementation of product development and prototyping functions). Considering the functions made in the environment, the goal was to integrate the environment into several courses and student projects. By integrating the RDI-functions of the University to the environment, it enables e.g. industry and company cooperation through projects.

As for the technological foundation, polymer-based 3D printing technologies (FDM, SLA and SLS) with multiple printers were selected because they are the most widely used technologies (Statista, 2020). Multiple printers enable the work of multiple students or groups at the same time and make the environment more versatile for learning purposes. The aim for this is the efficient learning of additive manufacturing through multiple technologies so that the students would gain knowledge from different technologies.

From self-learning point of view, the goal was to give the students the possibility to perform independent printing projects in the laboratory (this requires proper training before they can use the equipment independently, the students must perform the so-called "driving licence" to enable independent work). The laboratory is equipped with access control; access can be monitored and personal access rights can be granted to students. The process of creating the new 3D printing laboratory is presented in Figure 4.

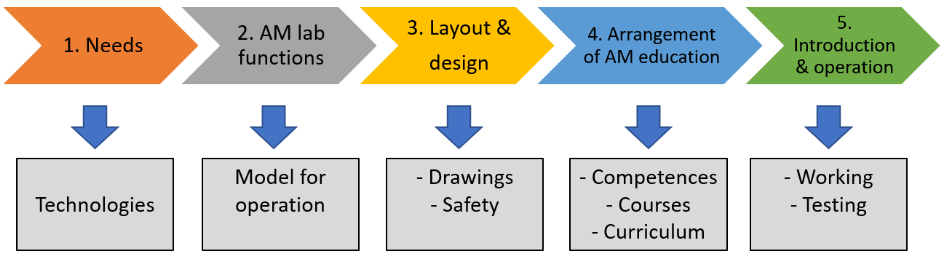



**Figure 4**: Process for creating Lapland UAS 3D printing laboratory

As presented in Figure 4, ***the first stage*** presents listing of the needs for the operation in the laboratory. This is based on the experiences from previous courses and the student feedback. The Smart Lab project goals, considering the needs of the industry and companies, was included in this stage. The Smart Lab project included the company and industry participation as their representatives were included in the project´s executive team. This led to the selection of the three AM technologies: FDM, SLA and SLS of polymers and they were proved to be suitable technologies for the purposes of educating mechanical engineers based on the statistical information. ***The second stage*** consisted of creating a model for the operation in the environment. This was crucial since the laboratory will be connected with several other functions in the Smart Lab environment. The model will work as a roadmap for operation in the 3D printing laboratory. This model will be presented in the next section of this study. ***The third stage*** included the practical design work for renovating the new space for the laboratory. This included electrical, air exchange and layout design work. This was done together with the Lapland UAS mechanical engineering staff and with the designers of the actual space renovation. This stage included the safety factors presented in this study. ***The fourth stage*** included implementing additive manufacturing into the mechanical engineering curriculum. This means including AM in different courses and projects through drafted competences and learning objectives. This part includes a wide company questionnaire considering the requirements and needs for the AM education at Lapland UAS. The questionnaire is not part of this paper since it will be the next stage in making the environment fully operational in several courses. Through the questionnaire and previous experience, the competences and learning objectives will be created for the courses. ***The fifth*** and final stage includes the introduction of the environment by testing all the equipment and making them operational. It also includes the wide introduction of AM in courses, student projects and RDI-functions. The collection of feedback from this stage is important for further development of the environment and the AM education. This is also part of the next stage and is not presented in this study.

### 4.3 3D printing laboratory functions

One main factor in designing the new laboratory was the creation of a model representing the connection of the 3D printing laboratory to other functions in the Smart Lab and the Lapland UAS mechanical engineering degree programme. This includes pointing out subjects for research for future purposes. As stated in this study, the current literature does not provide a clear process or model for designing this kind of environment or planning the functions in bigger scale such as connecting an existing 3D printing laboratory to a wider functional entity. It is important to provide a model how to connect an existing 3D printing environment to other contexts such as design system in engineering or to a manufacturing process chain. Therefore, a ***functional model*** for the 3D printing laboratory was created for this study from educational point of view. The model consists of three sections: ***3D printing laboratory and the functions***, ***the outputs*** from these functions and last, ***the engineering education*** section. All of the presented research topics are meant to work as a substrate for the research in the environment for future purposes. This model gives also an example for integrating 3D printing environment into a wider functional entity in HEIs´ or in companies. Figure 5 presents the first section of the model.

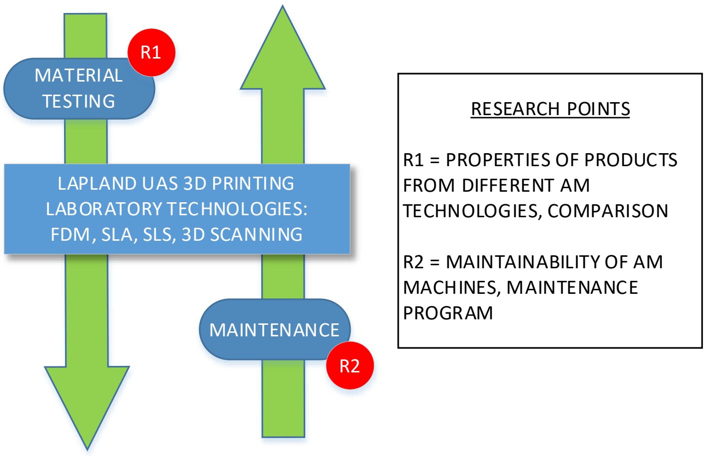



**Figure 5**: 3D printing laboratory section from the function model

As presented in Figure 5, the **3D printing laboratory** forms the foundation for the operation. Engineering education and the RDI-groups form the user base for the laboratory. Different 3D printing courses are held in the laboratory and RDI-personnel perform research and work connected to different RDI-projects. In the background there are the material testing and maintenance know-how which present the two main functions of Lapland UAS RDI-operations. The green arrows present the cross-sectional operation; these two functions are realized in the education but also in the laboratory functions. The goal is to perform material testing with 3D printed parts and connect the printers to the Lapland UAS maintenance system for ensuring the operation of the printers. This gives the possibility for students to learn about the maintenance of the equipment. This also enables the practical training with a real-life maintenance system (e.g. with maintenance software). **R1** presents a planned topic for the research of material properties of different printed objects. **R2** presents a planned topic for the research of the maintenance of the printers and developing system for maintenance information and handling.

As an output, the functions in the 3D printing laboratory produce different kind of products for different purposes. This presents the second section of the model. Figure 6 present these outputs.

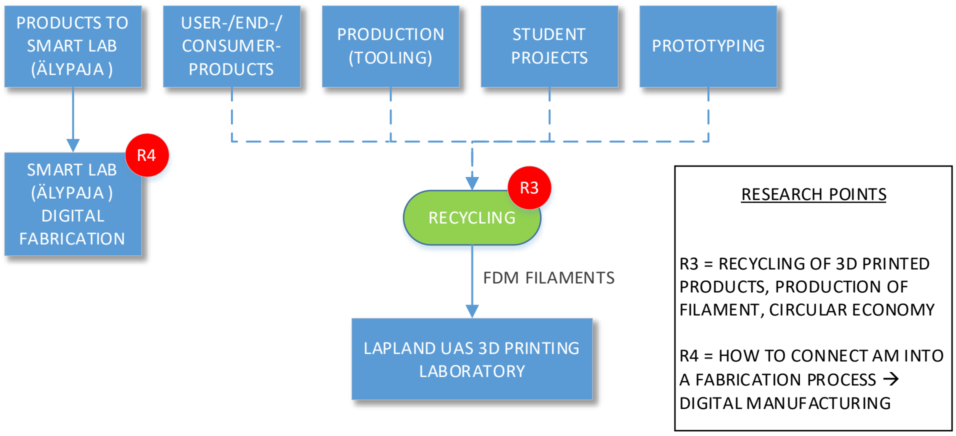



**Figure 6:** 3D printing laboratory outputs from the function model

As seen in Figure 6, the 3D printing laboratory outputs present the targets for different 3D printing applications such as products to Smart Lab meaning producing polymer parts for the digital manufacturing equipment (e.g. plastic parts to an assembly). The second output is the user/end-use/consumer products done via direct manufacturing of usable parts for different purposes. The third is production (tooling) which means manufacturing tools for production through other manufacturing methods (e.g. molds for casting). Concerning the learning aspect, the fourth output is the student projects. These are course projects and independent student projects where the students can also perform their own projects in the environment. The fifth output is prototyping which produces prototypes e.g. from mechanical products and assemblies and evaluating the product properties before the final design. One function will also be the recycling the printed parts through plastic shredding and filament fabrication equipment. **R3** presents a planned topic for the research of recycling printed parts (material properties, filament fabrication and the circular economy aspect of 3D printing). The filament fabrication and plastic shredder equipment enable the production of recycled filaments to be used in the laboratory. **R4** presents a planned topic for the research of different aspects of digital manufacturing and the integration of 3D printing into it.

The third section is the engineering design aspect of the model as presented in Figure 7.

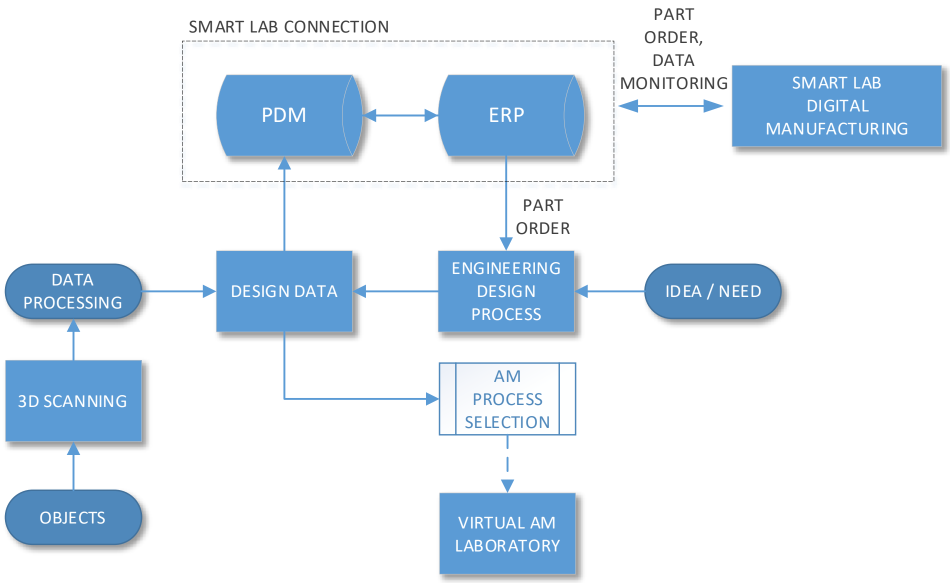



**Figure 7**. Engineering design aspect from the function model

As seen in Figure 7, the traditional mechanical engineering studies are included in the studies of the students before they are scheduled to work in the laboratory. These prior studies include learning the engineering design process and the production of design data which produce the necessary information for 3D printing (e.g. 3D modelling, calculations and design aspects). The engineering design process can be seen as a starting point since the product idea or need starts the design process. This stage includes also the 3D scanning possibility (re-engineering products through possible part optimization) which is a vital part of modern engineering. Considering the nature of the 3D printing technologies in the laboratory, the material sets limitations what kind of parts and products can be e.g. re-manufactured. This information will be handled in the AM process selection model which aims to select the most suitable 3D printing technology for the part. This is not presented in this study since it is a part of a different research done parallel with this study. A virtual version of the laboratory will also be created for orientating the user to the laboratory operations and especially safety (this will be a part of the "driver licence" training for the student to be able to gain independent access to the laboratory). This is not a part of this study as it will be designed and executed after the whole laboratory is finished (the laboratory is under finalization during writing this study). The digital knowledge transfer is done through ERP and PDM systems. The design data is stored in the PDM systems' product and part catalogue. By using the ERP system, the parts can be ordered as in real life manufacturing process. This simulates real life design system where a product order starts the design process. These systems connect the Smart Lab to the design data through part order functions and data monitoring (e.g. monitoring the materials in the Smart Lab material storage which can be used in fabrication). These are not presented here since they are part of work package 3 as presented in Figure 3. These three sections combined form the functional model for utilizing 3D printing as a part of education and manufacturing process. Figure 8 presents the three sections combined.

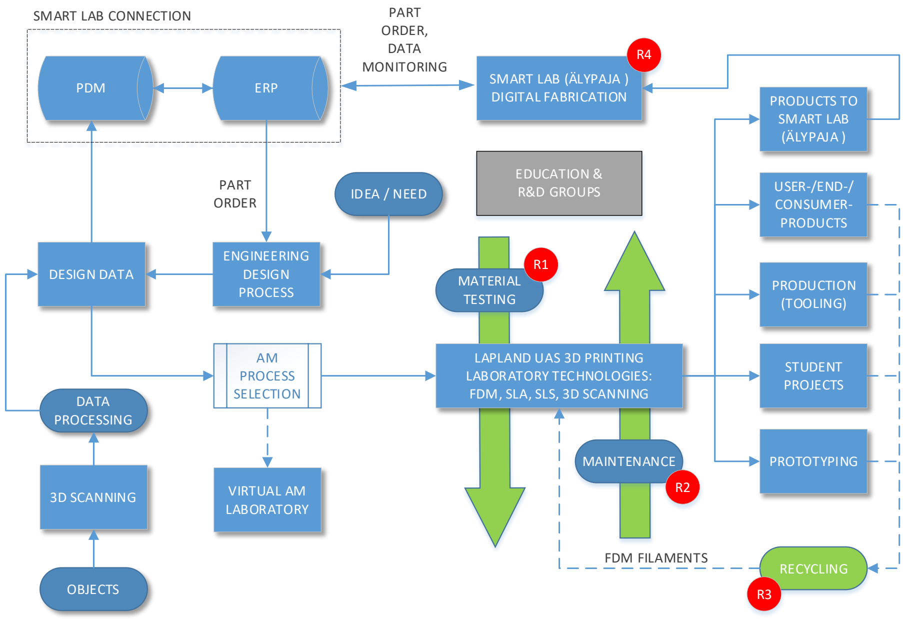



**Figure 8**: 3D printing laboratory function model

As seen in Figure 8, the 3D printing laboratory is in the centre of the operation and all the function flows are presented with arrows. The model shows how the outputs from the 3D printing laboratory connect to other function and it shows the connection to the Smart Lab and to the engineering design and education through PDM and ERP systems. The model presents the path from idea to a product where the product idea or order is processed in the engineering design process which produces 3D model for 3D printing purposes. The AM process selection enables the selection of the most suitable 3D printing technology for the product. The final product forms either in the 3D printing laboratory (when producing finalized and usable 3D printed parts) or in the Smart Lab where the 3D printed parts are part of an assembly. This model can be used as map for all the functions that the 3D printing laboratory enable and therefore benefit companies and other HEIs´ in their development work with similar environments.

### 4.4. Layout & design of the laboratory

The designing of the new laboratory was connected to Lapland UAS Kemi campus renovation, which took place in 2019 modernizing the campus and the learning environments. One part of this was the renovation of the new Smart Lab facilities and the new 3D printing laboratory. The designing of the new laboratory was based on the experience from the previous laboratory and to research from existing 3D printing laboratories. It included also visits to different 3D printing laboratories in Finland and Europe. The design work started from scratch, the origin was a classroom with the space of $86m^2$. The planning of the laboratory included the involvement teaching, RDI-staff and students. The student feedback was collected from previous 3D printing courses for this purpose. The designing of the occupational safety (air extraction and chemical safety) is based on the research results presented in section 2.2. and to general safety regulations for university environment. This study does not include the measurement e.g. for the emissions since the laboratory is on its design phase during the writing of this paper. This will be further studied when the laboratory is fully operational and all the safety equipment has been built, installed and tested to be functional.

The layout design work included the following parts:

- Electrical design (places for sockets, lightning, IT-sockets, audio connection for 75″ LCD monitor). A map for required places for e.g. sockets was made and handed out to a professional electrical designer who made the official designs.
- Air extraction design (main air duct, the placement of the air extraction spots, the control of the air extraction valves, the timing possibilities of the air extraction). This was done in cooperation with HVAC designer who planned the details based on the information about the required extraction points and preliminary air rates.
- Furniture design (places for tables, chairs, cabinets etc.). This was based on the layout design where the space was made to be as functional as possible enabling versatile work in the laboratory.
- Logistical operation in the space (e.g. the separation of technologies, integration on design work and actual printing, the working area around different targets). This was based on the research of existing 3D printing laboratories. The isometric presentation of the layout can be seen in Figure 9.

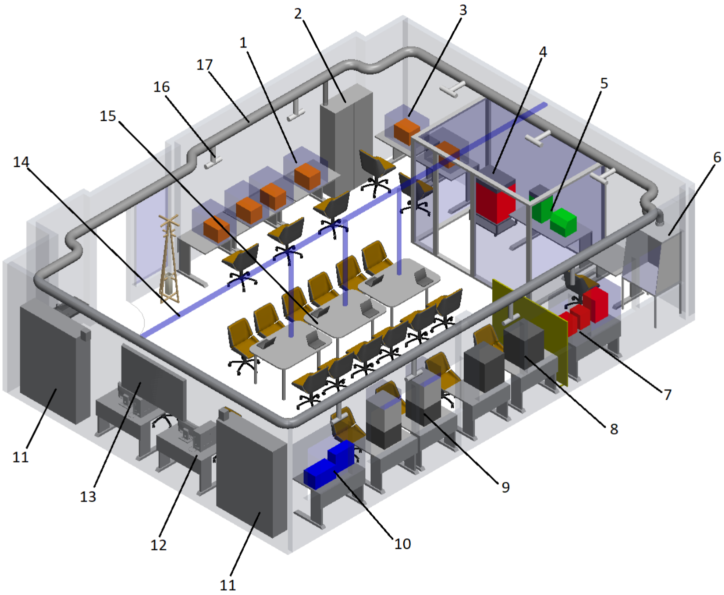



**Figure 9**: 3D printing laboratory layout

As seen in Figure 9, the laboratory consists of the following items:

1. FDM-printers. 4 pcs Original Prusa i3 MK3s, polycarbonate casings with a connection to the air duct with flexible hose.
2. Chemical cabinet, fire-proof. For storing hazardous and flammable chemicals and materials with a connection to the air duct rigid air duct.
3. FDM-printers. 2pcs Creality Ender 3 Pro, polycarbonate casings with a connection to the air duct with flexible hose.
4. SLS printer. 1 pc Sinterit LISA2 Pro. Separate space with laminated safety glass walls, ceiling and sliding door to prevent the powder drift to the laboratory. The space is connected to the air duct with separate ducts.
5. Sinterit Sand Blaster and Material Sieve station. Sieving the used powder with fresh powder and the post processing of the SLS parts with glass balls (abrasive material).
6. A ventilated chemical laboratory cabinet. With a closable glass door for post processing (painting, sanding, IPA washing etc.) with a connection to the main air removal duct with a rigid air duct.
7. SLA-printer. 1 pc Formlabs FORM 3 with FormWash and FormCure, a polycarbonate casing with doors and a connection to the air duct with flexible hose with doors.
8. Closed FDM-printers. 2 pcs Minifactory Innovator L with a connection to the air duct with flexible hose. The hose is connected to the printer air outlet with a connector part.

9. Closed FDM-printers. 2 pcs Ultimaker S5s´ with Material station and Air Manager with a connection to the air duct with a flexible hose. The hose is connected to the printer an air outlet with a connector.
10. Filament fabrication and plastic shredder equipment. With a polycarbonate casing with doors and a connection to the air duct with a flexible hose. The shredding of plastic products and the filament fabrication causes emissions, odour and dust particles.
11. Storage cabinets for filaments, tools etc.
12. Work stations for 3D modelling and laser scanning.
13. 75″ LCD display (a wireless connection for laptops and mobile phones for display purposes).
14. Electrical feed from above (blue line). The sockets can be pulled down via winch from above the tables.
15. Innovation and group work area.
16. T-joints for the air extraction spots. Timer-controlled, automatic valve with an on/off switch for continuous air extraction and iris valves for adjusting the air flow per extraction point. A flexible air hose from the extraction point will be connected to the joint.
17. Main air removal duct. The fan is situated outside of the university and the exhaust air is ventilated through a separate ventilation system (it is not connected to the buildings HVAC-system). The duct goes around the whole room and enables future expansion for more printers/equipment.

The design of air extraction from the printers was separated as student project work. The goal was to design and build closed casings to all the printers and connect the casings to the main air extractions duct via flexible air hose. The research presented in Kim et al. (2015) and Floyd et al. (2017) show that desktop-level FDM printing causes emissions that are hazardous to health and proper actions should be made. The usage of filters or other measures to block the emissions present to be the minimum action to be made. The most efficient way to handle emissions during 3D printing is to build completely closed casing around the 3D printing (Viitanen et al., 2016). This was kept as the starting point for the design. The second was the operation with the printers; the casing should not prevent work with the printer (e.g. material loading and removing the print). The principle of the design is presented in Figure 10.

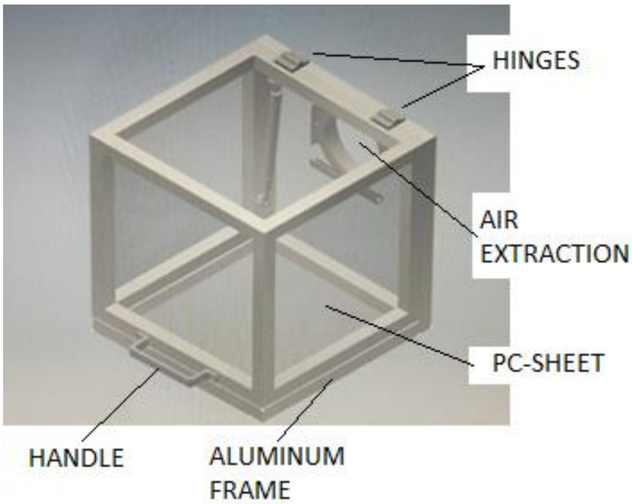



**Figure 10**: The design for closed aluminium/PC-casing for open FDM-printers (Lapland UAS student work)

As presented in Figure 10, the frame for the casing is made from an aluminium profile with polycarbonate sheet attached to the main groove of the profile. The size of the casing can be changed according to the printer and this design is meant for the open type printers such as iPrusa. The structure consists of two pieces; the lower is attached to the table and the upper can be lifted via hinges whenever needed to access the printer (e.g. during printer setup and filament insertion). During the printing, the casing is closed and the air in extracted through the exhaust joint and flexible air hose. There is a possibility to add a filter (e.g. HEPA) to the exhaust joint in order to remove fine particles from exhaust air to the main air duct. The air extraction rate is adjusted for each casing through the air extraction iris valve (see number 16 in Figure 9) of the main air duct. This causes negative pressure inside the casing ensuring the handling of particle emissions and odours during print. This will be adjusted during the testing phase of the printers to match the required air flow in order to remove particles. Replacement air is taken through the gaps in the structure (between the two pieces).

The SLS, SLA printers, filament fabricator and plastic shredder are encased with a bigger casing principle as presented in Figure 11.

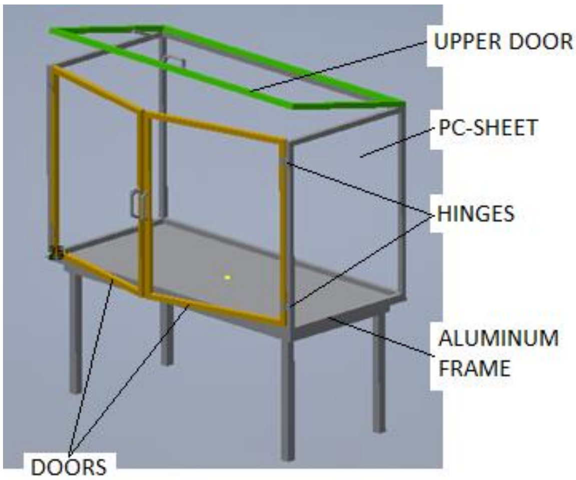



**Figure 11:** The design for closed aluminium/PC-casing for SLS/SLA printers (Lapland UAS student work)

As seen in Figure 11, the design consists of frame and doors. This design enables the user to reach the printer during the off-print. The design principle can work also with an upper door if there is a need to access the equipment from above (e.g. with Sinterit LISA2 PRO or if a FDM machine has to be accessed better). In Figure 11, the casing is installed on top of a table (e.g. for FORM 3) but it can be constructed also straight to floor with minor adjustments. E.g. the size of Sinterit LISA2 Pro requires rather low installation height for the printer so the table is not needed. The casing can be built around the printer enabling the usage of the printer and preventing the powder from spreading. A note can be made that a knurled or corrugated rubber mat should be installed to the floor which prevents the powder from spreading from the floor level. As with the open FDM-printers, the air extraction works with the same principle. An air extraction point will be installed to the correct place through testing the best air flow paths with the printer.

## 6. Conclusion and recommendations

The current literature and research do not provide solid instructions about how to build an occupationally safe and functional 3D printing learning environment from educational point of view. Every HEI using 3D printing performs it in their own way, usually based on common rules, examples and occupational safety regulations. This study presents necessary factors such as chemical safety and emission safety needed to be considered in designing a functional and safe 3D printing laboratory. Studies have showed that particle emissions especially in nanoscale causes a risk to health. Therefore, a proper designing for completely casing the open-type printers must be implemented in order to achieve safe learning circumstances. Also, the printers with their own casing and filtered air outlet must be connected to a separate air extraction system. The only completely sure solution for implementing the occupational safety of 3D-printing is to have 0 % of emissions and odours to the laboratory space. When designing a 3D printing laboratory, this should be the only acceptable target for occupational safety. When the functionality of a 3D printing laboratory is designed, the environment must be defined closely and the design work should be based on to the requirements set by education and work-life. These demands are always on the background when planning the contents of e.g. engineering education.

The design work can be divided into two parts. First there is the so-called design phase based on engineering design which considers the designing of layout, electrical installations, air extraction and general operational logistics. This gives the structural foundation to the 3D printing learning environment.

The second part consists of planning the operation in the environment which connects the 3D printing laboratory with other necessary functions (here the Smart Lab is the target but this can be expanded e.g. to the operations of a certain company or university environment). This gives the foundation for the learning in the environment. The model for the 3D printing laboratory operation shows that 3D printing must not be seen as an individual entity but more as a part of larger operational whole (e.g. as a part of the path from idea to product). The environment must also support the self-learning aspects through the possibility for the student to work independently in the environment. This requires proper orientation to the 3D printing technologies from theoretical and practical point of view. This includes also knowing the safety factors and working according to regulations and instructions. The students must have controlled and independent access to the laboratory in order to enable independent projects together with school projects. By allowing the student to perform project learning based on their own needs, it will increase the motivation to learn more and therefore develop into a 3D printing expert.

The future development of the laboratory includes offering the 3D printing functions to outside of the University. This includes short-term courses for companies and to other interested parties in order to spread the information about the possibilities of the technology. The participation of the RDI-functions ensures also the cooperation with different companies in their development projects. The laboratory offers a lot of research targets (as presented in Figure 8) which enables also a substrate for theses. The continuous development of the laboratory is important due to the fast development pace of 3D printing technology. This requires investments in the future and the development of expertise in this area. 3D printing laboratory as a learning environment offers a versatile, functional, innovative and motivational possibility for students to learn engineering principles and develop into an expert in their own field.

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# Publication IV

Pikkarainen, A., Piili, H., and Salminen, A.
**Introducing novel learning outcomes and process selection model for additive manufacturing education in engineering**

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# INTRODUCING NOVEL LEARNING OUTCOMES AND PROCESS SELECTION MODEL FOR ADDITIVE MANUFACTURING EDUCATION IN ENGINEERING

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**Abstract:**
Additive manufacturing (AM) is at the verge of being recognised as one of the main manufacturing methods among the traditional ones. The largest obstacle in using AM in the companies is the lack of knowledge about the possibilities of the technology. One sub-problem caused by this is the lack of qualified machine operators in companies due to the insufficient AM education. This indicates the need for strengthen the current AM education especially in the B.Sc. and M.Sc. levels in engineering education by emphasising the importance of AM in curriculum development. This study presents novel learning outcomes based on the needs of manufacturing industry and companies in Finland. A questionnaire was conducted to work-life representatives in order to map the requirements for AM education in the mechanical engineering degree of the Lapland University of Applied Sciences in Finland. The responds were collected as competences representing different areas of AM knowledge and the learning outcomes were derived from the responds. AM education must also provide a model for selecting the most suitable AM technology in order for students to learn the technological aspects. This study also presents a process selection model which can be used in AM education. The model allows the student to compare different AM technologies from different perspectives such as material, functionality and visual appearance point-of-view.

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**Keywords:** additive manufacturing, 3D printing, curriculum, learning outcome, engineering

## 1. Introduction

This study presents the creation of learning outcomes for the education of additive manufacturing (AM) based on the requirements and needs of work-life in the field of manufacturing industry in Northern Finland. The study is based on a questionnaire and its results conducted to selected work-life representatives. In addition, a novel process selection model for selecting the most suitable AM technology is introduced in this study. The model is especially meant for users in the beginning of AM learning path to facilitate the selection between the most suitable AM manufacturing process. The creation of the model is based on research work from the field of AM. AM is a manufacturing method where data is extracted from 3D model in layers. This data is then used in the AM process where material is joined together layer by layer with selected technology. The term AM is officially used when discussing more advanced and expensive industrial type of 3D printers. The synonym for AM is 3D printing which is usually connected to AM equipment below the classification of these more advanced and expensive printers (SFS-EN ISO/ASTM 52900, 2017).

The success of AM is growing, especially when looked from market point-of-view. Between 2017 and 2020, the incomes of companies connected with AM have doubled which presents the growing importance of AM as one of the manufacturing technologies. In a survey conducted to 187 people working in companies in the Nordic and Baltic countries, 84% of the respondents had sufficient knowledge about AM in their own opinion and 65% saw the potential of AM in business. Despite this, it was noticed that there was a lack of information about the design principles and the price of the technology was an obstacle. The largest impacting factor to utilizing AM in as business, was the print quality (PLM Group, 2019). This shows that the basic principles seem to be in order in general level but the need for the education of AM concerning especially more detailed information about AM is needed. Therefore, this study concentrates especially in the needs and requirements addressed to the engineering education which come from the industry and companies in Finland. From educational point-of-view, AM brings practical content to the learning process by offering the possibility learn by doing. AM brings extra value to learning in many educational areas such as medical and engineering as presented in (Ullah et al., 2020; Chen et al., 2020; Wang et al., 2020 and Ford et al., 2020). The manufacturing sector is at the verge of realizing the full potential of AM in their operations. This can be seen as an increased need for the AM machine operators which automatically leads to the need for educating them e.g. during engineering studies. The demand for using the technology has increased from single manufacturing events into a complete AM process starting from CAD designing into the post-processing. 3D scanning is seen as an important part of the AM process since it offers the possibility of re-engineering parts in many areas (PLM Group, 2019; Jiang et al., 2016 and Paulic et al., 2014). For this reason, the model for AM process selection presented in this study contains 3D scanning as a substrate for 3D model. Important note based on the experience of the authors is that even though 3D scanning is a good method to be used in the AM process, it cannot image the internal shapes of the part. This requires always proper 3D modelling.

### 1.1 Aim and purpose of this study

This study is focused on the creation of novel learning outcomes for learning AM based on the needs of the work-life. The main motivation for this study is the lack of proper arrangement of AM pedagogics in the literature especially when implementing AM courses in curriculum. This study is based on literature review and to the experience of the authors as educators in the area of additive manufacturing. A quantitative questionnaire was targeted to work-life representatives to point out the needs and demands for AM teaching and learning, especially from learning outcome point-of-view when implementing AM into an engineering curriculum. The arrangement of mechanical engineering degree curriculum at Lapland University of Applied Sciences in Finland works as a platform in this study from pedagogical point-of-view.

These learning outcomes can be used in engineering education in creating up-to-date AM education which meets the demands of companies and work-life representatives who are using or planning to use AM in their functions. In addition, this study presents a process selection model for learning the principles of FDM, SLA and SLS printing. This process model gives the possibility for a student to select the most suitable AM process for polymer printing from these three technologies which represent the most used AM technologies at the moment (PLM Group, 2019 and Statista, 2020). These learning outcomes and process model can be used when implementing AM into engineering education.

## 2. Literature review

Curriculum is a plan for arranging education consisting of information about how to define and guide learning, teaching and education. It gives the roadmap for arranging learning events in a certain degree (Karjalainen et al., 2007). One of the main factors in curriculum work is to apply different recommendations and regulations. In Europe, this is based on the National Qualifications Framework (NQF). NQF combines the degree systems of European Higher Education Institutes (HEIs´) and gives a common platform unifying the regulations of the degrees. NQF consists of eight different levels which present the education level in Europe (from basic education to doctoral degrees) (Auvinen et al., 2010; Lapland UAS, 2015 and FNAfE, 2020). Levels 6 (B.Sc.) and 7 (M.Sc.) are in focus and this study is based on the curriculum renewal process of the Lapland UAS mechanical engineering degree which took place in 2014 - 2017. This study concentrates on only to the definition of competence groups and learning outcomes concerning AM education and not to the whole curriculum process. The reason for this is that one main goal of this study is to present learning outcomes for AM education needed in implementing it into engineering curriculum. The curriculum process has been presented in the previous stage of the Lapland UAS mechanical engineering curriculum work preceding this paper (Pikkarainen and Piili, 2020). The outcome of the process was a new curriculum which started in the Fall of 2017. The aim of the renewal process was to create a knowledge and problem-based curriculum by the real needs of work-life.

One of the main tasks of a curriculum is to set outcomes for education. These are called the learning outcomes which define what the student has to know and understand after the course. The learning outcomes are categorised into different competence groups. Competences are a set of learning outcomes which collect all the required knowhow and skills from each competence group. Competences are usually divided into general competences and subject specific competences. Therefore, it can be said that one competence group contains a set of learning outcomes derived from that competence group. This study concentrates on only to the subject specific competences since generic competences are defined in degree recommendations set by an educational agency (in Finland, the Rectors´ conference of Finnish Universities of Applied Sciences, ARENE). The subject specific competences are the ones that are implemented as substance-based topics into the courses (e.g. 3D printing which as a term is more familiar to students than AM) (Auvinen et al., 2010). The definition of the learning outcomes is important since they include the demands for learning from the work-life point of view. Drafting the learning outcomes require research work and versatile analysis of information coming from different directions such as society and work-life (Lapland UAS, 2017 and Honkala et al., 2009). The foundation of the learning outcomes dates back to 1956 when Bloom's taxonomy model defined six different categories for describing educational objectives, especially for educational purposes. The categories are knowledge, comprehension, application, analysis, synthesis and evaluation (Bloom, 1956). These categories can be seen as a path to advanced learning. Figure 1 presents the categories.

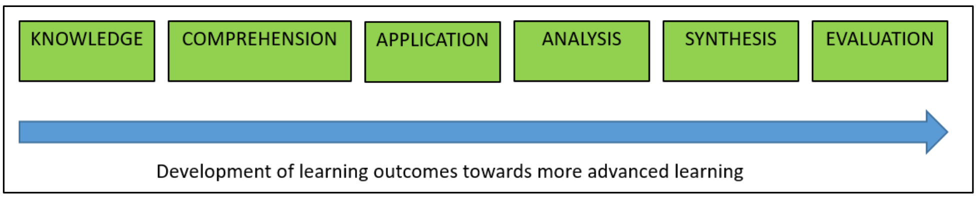


**Figure 1**: Development of learning outcomes according to Blooms´ taxonomy
(Applied from Bloom, 1956; Arapi et al., 2007; Meda and Swart, 2017; Stanny, 2016)

As seen in Figure 1, the following present examples, how the categories of the taxonomy can be used in defining an outcome for learning or e.g. skill to be acquired. These explanations can then be derived into actions the student must take in order to achieve a desired target in learning (Applied from Bloom, 1956; Karpen and Welch, 2016):

- *Knowledge*: to possess information and understand it (e.g. writing the laws of Newton)

- *Comprehension*: to understand the meaning and nature of information (e.g. explain the nature of gravity)
- *Application*: to have the ability to use and apply the information in different circumstances (e.g. arrange an experiment demonstrating gravity according to Newton's laws and demonstrate the main results numerically)
- *Analysis*: to be able to analyse e.g. the nature of a problem and find the factors related to possible solution (e.g. explain and analyse the effect of gravity on the part when external supports are removed)
- *Synthesis*: to combine information and e.g. ideas into solutions (e.g. produce a new learning task presenting different aspects of gravity)
- *Evaluation*: to be able to evaluate action or the nature of the solution based on to the students´ thinking or cognitive factors (e.g. select the most efficient and profitable way to perform the gravity experiment according to the preliminary test results and compare pros and cons).

In the first category *knowledge* the student acquires information for learning purposes where as in *evaluation* the student is able to evaluate and even justify his/her own learning. As these examples present the actions to be made, the creation of desirable learning outcomes requires measurable verbs to describe these functions. When the verbs are connected to the different levels of the taxonomy, the learning outcomes can be classified more specifically. Based on the experience of the main author, this way the planning e.g. of course contents, can be done more specifically when knowing what the student has to learn or to be introduced to. It shows the importance of each specific subject; what are the topics that must be emphasized in a course in theoretical form and what topics can be presented e.g. through practical methods such as laboratory work. The following presents an example of using these verbs in describing learning outcomes (Applied from Bloom, 1956; Arapi et al., 2007; Meda and Swart, 2017; Stanny, 2016):

- *Knowledge* (The student knows and can describe the laws of Newton)
- *Comprehension* (The student is able to recognize the situations where gravity takes place)
- *Application* (The student can demonstrate the nature of gravity through examples)
- *Analysis* (The student can analyse the results from gravity experiment and differentiate the different Newton laws occurring during the experiment)
- *Synthesis* (The student can combine different aspects from the laws of Newton and construct new kind of examples presenting them)
- *Evaluation* (The student is able to compare different ways to measure gravity and select most viable and appropriate method for the measurement).

Based on the experience of the main author, these verbs included in the description of the learning outcomes help the educators in planning the detailed contents of courses. They describe the desirable target for the students´ level of learning from certain subject and therefore are important factors in planning the implementation of AM into an engineering curriculum as presented in this study. When the creation of learning outcomes is looked from a curriculum process point of view, the following stages can be noticed according to (Honkala et al., 2009):

- Analysing existing curriculum: compare the goals of the courses into the goals of the curriculum
- The description of achievable knowhow: after the completion of the course, what the student knows and can do
- The creation of the learning outcomes: learning outcomes must be written into a form which describes well the know-how of the student after the completion of a course
- Assessing the course descriptions: after the creation of the course descriptions in the curriculum, the descriptions are analysed by teachers. In this stage the quality of the course contents with respective to the curriculum are inspected.
- Assessing the learning outcomes: at this stage, the result of the learning is assessed. If the learning outcomes have been achieved, the student passes the course with accepted grade. One important part of the process is the grade criteria; the learning outcomes are assessed with respective to the criteria. This gives an insight how well the students have achieved the desired learning outcomes.

This study consists of the stage three where the learning outcomes are created. The stages one, two, four and five are part of the Lapland UAS mechanical engineering curriculum work which is not presented in this study.

## 3. Arrangement of AM education in Lapland UAS mechanical engineering curriculum

The curriculum of Lapland UAS includes AM in different courses and projects. The implementation of AM to the curriculum was done through taking the needs of companies and industry into account with a separate questionnaire presented in this study. It includes the experience of lecturers and research and development (R&D) personnel. Most of the AM studies have been embedded in separate courses and semester projects. Table 1 presents the listing of selected courses and projects for AM purposes.

AM knowledge and experience increases

| Semester | Course name | Type of learning of AM | AM technology | ECTS |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | Project: Product development | Theoretical, design work<br>Theoretical | FDM<br>All | 1<br>5 |
| 4 | Project: Prototype<br>3D Design of a product | Practical<br>Theoretical and practical | FDM | 2<br>2,5 |
| 5 | Work-life project | Theoretical and practical | FDM, SLA, SLS | 5 |
| 6 | Project: Finding solution<br>3D Printing and applications | Theoretical and practical<br>Theoretical and practical | FDM, SLA, SLS | 5<br>5 |
| 7 | Project: Innovation<br>Future technology | Theoretical and practical<br>Theoretical and practical | FDM, SLA, SLS | 5<br>2 |
| 8 | Bachelor thesis | Theoretical and practical | FDM, SLA, SLS | 15 |
| | | | **MAX TOTAL** | **47,5** |

**Table 1:** Lapland UAS mechanical engineering AM studies in courses and projects

As presented in Table 1, the AM education is connected to courses and semester projects and it presents the maximum amount of possible ECTS points which the student can study AM topics within a course or project. One course or project is always 5 ECTS so it can be fully or partially connected to AM topics. One aim for this study was to create learning outcomes for these AM topics in order to make them to be based on the needs of the work-life and companies. The amount of credits can change according to the topics of the projects and in B.Sc. theses subject, this table presenting the estimated maximum amount of AM the student can study through the curriculum. When looking at the projects, there are always different topics for student groups, some of them linked to AM. This means that since in projects, student groups have different topics, the whole student group does not always go through the same learning path. This enables the possibility for a student to select maximum amount of AM studies, therefore each student can affect their own learning path considering the field of interest and to the professional development. The B.Sc. thesis can be linked to AM completely if the topic connects with the technology. In addition, the students can work in the AM laboratory independently making their own projects. This has been seen as major factor in the Lapland UAS in increasing the motivation of the students towards AM subjects. In addition, Table 1 presents the type of learning (theoretical education of AM or practical work on the laboratory) and the polymer printing technology used in the course or project. As seen in table 1, FDM is used in the beginning of the printing process because of its relatively easy usage and introduction into practise based on the experience from the previous AM courses in the Lapland UAS mechanical engineering degree. This is used for building the experience of the student about AM before introducing more advanced technologies such as SLA and SLS. This relates to the inversely proportional learning of AM. The course structure supports the learning in the beginning with simpler FDM technology and it allows the student to increase the knowledge of AM towards the graduation with more advanced AM technologies and situations such as independent projects or even customer cases (Pikkarainen and Piili, 2020).

## 4. Methodology

The next stage was to integrate the desired learning outcomes to the content of the courses. A separate questionnaire was sent to representatives of companies and industry targeting to find out the need for arranging AM education in the Lapland UAS mechanical engineering degree. This takes the needs of work life into account when planning the AM education. The questionnaire was performed with Webpropol software via hyperlink sent to different representatives in the region of northern Finland. In addition, the link was sent via forums to companies linked with AM situated in the region of southern Finland. Business sectors of the companies were selected according to the Lapland UAS mechanical engineering degree contents. The sectors were: machine- and equipment production and installation, piping production and installation, product development, industry (the manufacturing of metal, pulp and paper) and AM. The questionnaire was arranged anonymously to protect the information of the companies. Total of 56 responses was received. It can be stated that the questionnaire was arranged during spring 2020 when the COVID-19 pandemic was at its first wave in northern Europe at this clearly affected the number of responses when companies and industry were facing new kind of challenge in their operations.

The questionnaire collected some basic information from the responders (n=56) in order to identify the basic functions of the companies and to get a view about the responders. The term 3D printing was used in the questionnaire because of its popularity as a general term. The responders were allowed to select more alternatives per answer, hence the greater number of responds compared to the number of responders. The questionnaire contained questions whether the responder use or produce 3D printing services of not. Despite the answer the responder was allowed to continue in the questionnaire in order to collect information and opinions about 3D printing in general. This information gives an insight whether the company uses 3D printing primarily or secondarily in their functions. This refers to the employment options for the student specialized in 3D printing. The analysis of the basic information shows that the division between the usage, production or need for 3D printing is quite even. Basic 3D printing operations such as printing work, post-processing and design work are regarded as the most important operations in the manufacturing process. Companies informed that the most needed information about 3D printing were design principles, knowledge about the technologies and materials, possibilities provided by 3D printing for the company and last, the price factors behind 3D printing. Appendix 1 presents the details from the basic information from the responders.

The second part of the questionnaire consisted of 16 different questions where different areas concerning 3D printing and especially the needed know-how were mapped. The nature of the questions was selected according to the topics connected generally to 3D printing education. The aim of this was to receive an insight about the importance of the different factors. From these, the required learning objectives and competences will be analysed and written for the curriculum purposes. Figure 2 presents the arrangements of the questionnaire scale.

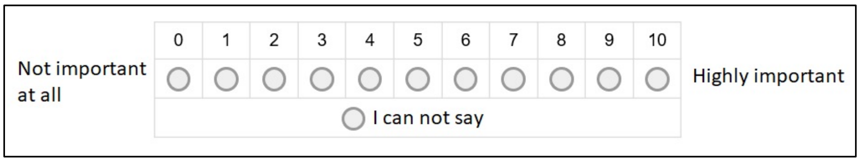


**Figure 2**: Questionnaire scale

As presented in Figure 2, a scale from zero to ten was used. The value zero presented the meaning “not important at all” and the value ten presented the meaning “Highly important. In addition, an option “I cannot say” (CNS) was included.

## 5. Results

The results were collected into a table format including the number of responses and their percentages. The scale from 1 - 10 was divided into three categories: from 0 – 6, 7 – 8 and from 9 – 10, the mean value of the responses was included. The number of “I cannot say” (CNS) responses was left out from the calculation of the mean value. Appendix 2 presents the numerical results from the questionnaire.

The answers were focused on to the scales from 7 – 8 and 9 – 10. This gives larger variation to the results than the normal 1 – 5 scale. For the analysis of the results, topics with mean value over 8.0 are considered important in this study. The lower mean value (e.g. 6 – 7) means that the topic is not so important or familiar to the companies. Since the topics of the questionnaire were selected according to the current 3D printing topics, these lower value responses can be seen as something that could be introduced to the companies through graduated engineers as they are employed to the companies.

The following conclusions can be drawn from the responses:

- The basic information of 3D printing e.g. different printing technologies, additive manufacturing (AM) process and basic principles are considered very important. Besides the mean value of 8.2, the percentage of 9 – 10 answer is 52.83%. This shows that the basic education (including theory and practise) is very important since from education point-of-view, this forms the foundation of 3D printing knowledge.
- 3D printing with metal is more important; this is because of the fact that mechanical engineering in northern Finland focuses more on metal industry (through the production of stainless steel and the companies connected with metal

manufacturing). Even though the situation is this, based on the experience of the main author, working with polymer materials in the beginning of the 3D printing studies presents easier start to the studies because of to the nature of the material. Printing with polymers present e.g. shorter build time, the level on required expertise is lower and post processing is simpler.

- Design principles (e.g. DfAM = Design for Additive Manufacturing) are considered very important.
- The special features of modern 3D modelling such as the structural optimization according to strength and reducing the number of parts (part consolidation) in assembly are important. Based on the experience of the main authors, these are topics that fit well into 3D printing because of the fact that they are a part of engineering design principles. By connecting the engineering design principles with 3D modelling, 3D printing brings an excellent way to visualize the principles in real-life (learning by doing).
- The usage of 3D printing in the functions of the company or industry is considered important. This included noticing the possibilities of using 3D printing e.g. in part manufacturing and also defining the viability of 3D printing in the product manufacturing processes.

When looked at the responses with a lower number of importance, the following conclusion can be drawn:

- The 3D printing of polymers and its possibilities is seen less important than the one of the metals. One reason for this is that in the region of northern Finland, metal industry plays a major role in the manufacturing industries.
- Companies are not willing to arrange joint projects with the engineering education. Possible reasons for this are the lack of resources for the cooperation (time and personnel) and the lack of connections to the University. In addition, the COVID-19 situation during the moment of the questionnaire can affect the current motivation to perform joint projects. Functional cooperation requires a personal connection to the company so that both sides commit to the project (Steinmo and Rasmussen, 2018).
- Recycling of 3D printed parts is still yet quite unknown, especially with polymer materials. This requires active research from the University so that the graduated engineers would have knowhow from this to be taken with them to the companies.
- Circular economy is still rather new topic in Finland. 3D printing offers possibilities to this, especially through part re-manufacturing and like with recycling, this is a topic that need to be supported in engineering education.

In addition, the questionnaire included a section for free form answer considering the following question: “What kind of expertise a future engineer needs regarding the usage of 3D printing in companies and industry?” From 56 responders, 21 gave an answer. The following presents the collected answers:

- The importance of 3D printing as a part of traditional mechanical engineering and the different applications of it. This includes the basic understanding of the possibilities and limitations of the technology.
- The design work for 3D printing should take into consideration the real operating conditions of the parts and products. This requires the understanding how machines work, for instance.
- The designer should be able to distinguish the meaning of 3D printing in a prototype, small series and mass production.
- The evaluation of the viability of 3D printing in the long run is important because of the fact that 3D printing will be more and more competitive in the future. This was included in the questionnaire which emphasizes the importance of this topic.
- Topology optimization and the recycling issues and circular economy will be greater factors in the future. This was included in the questionnaire which emphasizes the importance of this topic.
- The DfAM and topology optimization requires deeper understanding about material properties. The Finite Element Method (FEM) and surface modelling are important factors needed in the optimization. This was included in the questionnaire which emphasizes the importance of this topic.
- 3D printing of spare parts from even more sustainable material together with form optimization continues the life cycle of the product and saves costs.
- The possibilities of utilizing 3D printing in the region of Northern Finland are limited.
- Finding real and profitable 3D printing targets and needs is important.
- The basic know-how of 3D printing is something that needs to be in order (with polymers and metals) when an engineer graduate. This includes the basic understanding how the AM process (e.g. printing and post processing) affects to the material properties.
- The designer has to have basic understanding from 3D scanning.

These comments present important information about the tacit demands from work-life which should manifest in modern engineering education. The comments will be used together with the numerical responses in creating valuable information to the Lapland UAS mechanical engineering curriculum.

## 6. Analysis

The responses from the questionnaire form the frame for the creation of the required learning outcomes and competences in this study. These will be used in the Lapland UAS mechanical engineering curriculum and they can be used in other universities when planning AM courses. The target is to concentrate on AM of polymers because of Lapland UAS AM environment do not contain metal AM. Therefore, metal AM is viewed only from theoretical aspects. Table 2, 3 and 4 present the collected descriptions for the competence groups which have been derived from the questionnaire and the learning outcomes. In Table 4, the free word answers have been combined into more reasonable competence entities. The learning outcomes have been divided into six different categories based on the Blooms´ taxonomy. These categories help to place the learning outcomes in right courses since they present the level of learning at different levels (Applied from Bloom, 1956; Arapi et al., 2007; Meda and Swart, 2017; Stanny, 2016). In addition, the nature of the Blooms´ taxonomy enables the planning of the AM courses order in a way which grows the students´ knowledge about AM evenly during the studies.

| QUESTION TOPIC = COMPETENCE<br>Average > 8,0 | CATEGORY | LEARNING OUTCOME<br>(The student...) |
|---|---|---|
| 1. Basics of 3D printing<br>- AM technologies<br>- AM principles<br>- AM process | KNOWLEDGE<br>KNOWLEDGE<br>COMPREHENSION<br><br>EVALUATION | Can identify different AM technologies<br>Can define the AM principles<br>Is able to compare AM processes and distinguish them from each other<br>Can select the most suitable AM process for application |
| 2. 3D printing of metals<br>- technology, possibilities | KNOWLEDGE<br>COMPREHENSION | Can identify the possibilities of metal 3DP<br>Understands the basics of metal 3DP<br>Can differentiate metal 3DP from polymer 3DP |
| 3. Design principles (DfAM) | COMPREHENSION<br>APPLICATION | Understands the meaning of DfAM in design work<br>Can apply the DfAM principles in design work |
| 4. Optimization of 3D models (e.g. topology optimization, part consolidation) | COMPREHENSION<br>APPLICATION<br>ANALYSIS<br>SYNTHESIS | Understands the meaning of structural optimization in AM<br>Can perform str.opt. based on engineering design principles<br>Can distinguish the targets for optimization<br>Can design optimized structures for AM |
| 5. AM in companies<br>- utilization in company functions | EVALUATION | Is able to perceive the possibilities of utilizing AM in company functions |
| 6. Viability of 3D printing<br>Definition in the product manufacturing process | KNOWLEDGE<br>COMPREHENSION<br><br>SYNTHESIS<br>EVALUATION | Can define the viability in 3D printing<br>Understands the cost structure of AM and its relationship with viability in product manufacturing<br>Can develop profitable parts through AM<br>Can compare the different AM technologies cost-wise |

**Table 2**: Competences and learning outcomes derived from answers with the average of >8,0

| QUESTION TOPIC = COMPETENCE<br>Average < 8,0 | CATEGORY | LEARNING OUTCOME<br>(The student...) |
|---|---|---|
| 7. 3D printing of polymers<br>- technologies<br>- possibilities | KNOWLEDGE<br>COMPREHENSION | Can identify the possibilities of polymer 3DP<br>Understands the basics of polymer 3DP<br>Can differentiate polymer 3DP from metal 3DP |
| 8. Practical exercises<br>- polymer / metal 3DP | APPLICATION<br>ANALYSIS | Is able to use selected AM technology independently<br>Can choose the most suitable AM technology for printing |
| 9. Project learning<br>- common projects between education and companies | SYNTHESIS<br>EVALUATION | Can adapt the AM principles into real-life projects<br>Is able to compare the produced solutions and select the best alternative |
| 10. Recycling<br>- 3D printed parts and materials | KNOWLEDGE<br><br>COMPREHENSION | Recognizes different polymer materials and usage purposes for 3D printing<br>Understands the principle of recycling polymer 3D printed objects and filament fabrication |
| 11. Re-manufacturing (circular economy) | COMPREHENSION<br>ANALYSIS<br>SYNTHESIS | Understands the meaning of re-manufacturing of products<br>Can point out the possibility for re-manufacturing<br>Can design products according to the re-manufacturing principles |

**Table 3**: Competences and learning outcomes derived from answers with the average of < 8,0

| QUESTION TOPIC = Free word | CATEGORY | LEARNING OUTCOME<br>(The student...) |
|---|---|---|
| 12. 3D printing in engineering<br>- as a part of traditional mechanical engineering<br>- possibilities and limitations<br>- distinguish different applications<br>- reflecting into real situations (e.g into function principles of machines) | COMPREHENSION<br>COMPREHENSION<br>APPLICATION<br><br>ANALYSIS<br><br>ANALYSIS<br><br>SYNTHESIS<br><br>SYNTHESIS | Can illustrate mechanical functions through 3DP<br>Understands the possibilities and limitations of 3DP<br>Can identify the possibilities and limitations of 3DP in mechanical engineering<br>Can distinguish 3DP as a manufacturing method from the traditional ones<br>Can distinguish different 3DP applications (prototyping, small series, mass production)<br>Can combine 3DP into traditional mechanical engineering topics<br>Can adapt 3DP into real situations (e.g. mechanical functions) |
| 13. 3D printing and life-cycle<br>- spare parts and product life-cycle | COMPREHENSION<br>APPLICATION | Understands the role of 3DP in part life-cycle<br>Can identify the targets for spare part production through 3DP |
| 14. 3D scanning knowhow<br>- basic understanding and applications | COMPREHENSION<br><br>APPLICATION<br>SYNTHESIS | Understands the principle and possibilities of 3D scanning in 3DP<br>Can use 3D scanning in the production of data for 3DP<br>Can compile and covert 3D scan data into a format for 3DP |

**Table 4**: Competences and learning outcomes derived from free word answers

As seen in Tables 2, 3 and 4, the topics can be applied into many of the presented categories. This enables the usage of the learning outcomes in a more versatile way in courses. The goal is to build the AM knowledge along the semesters so that the more advanced learning happens in the later courses. The next step is the integration of the derived competences to the curriculum. This happens via competence matrix analysis where presented competences are linked to courses. The linking should be done in a way which supports the students´ development into an expert during the studies. This creates a list of competences which the student will possess during the studies and after graduation (Honkala et al., 2009). It creates the desired learning outcomes per course and helps to design proper course structure for AM education. When planning the detailed contents of courses, necessary learning outcomes can be selected from the competence groups. The term 3D printing is used also here. Table 5 presents the competence matrix.

| Semester | Competence matrix | 1. Basics of 3D printing | 2. 3D printing of metals (theory in Lapland UAS) | 3. Design principles (DfAM) | 4. Optimization of 3D models | 5. AM in companies and industry | 6. Viability of 3D printing | 7. 3D printing of polymers | 8. Practical exercises | 9. Project learning | 10. Recycling | 11. Re-manufacturing | 12. 3D printing in engineering | 13. 3D printing and life-cycle | 14. 3D scanning know-how |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | Project: Product Development | x | | x | | | | x | | | | | x | | |
| 3 or 4 | 3D printing (book exam) | x | x | x | | | x | x | | | | | x | x | |
| 4 | Project: Prototype | x | | x | | | | x | x | | | | x | | |
| 4 | 3D Design of a product | x | | x | | | | x | x | | | x | x | x | |
| 5 | Work-life project | | | x | x | x | x | x | | x | | | | | |
| 6 | Project: Finding solution | x | | x | x | x | x | x | x | x | | x | x | | x |
| 6 | 3D Printing and applications | x | x | x | x | x | x | x | x | x | x | x | x | x | x |
| 7 | Project: Innovation | | | | x | x | x | | | x | x | x | x | x | x |
| 7 | Future technology | | | | x | x | x | | x | x | x | x | x | x | x |
| 8 | Bachelor thesis | x | x | x | x | x | x | x | x | x | x | x | x | x | x |

**Table 5**: Lapland UAS mechanical engineering AM studies in courses and projects

As seen in Table 5, the competences have been linked to courses with the matrix table. On the vertical section, are the possible studies linked into 3D printing and in the horizontal section, the competence groups. This part of the curriculum work shows, what competences are achieved in certain courses and how the competences develop during the 4-year studies of the Lapland UAS mechanical engineering degree. When the detailed contents and description of a course are planned, the competence matrix shows what kind of targets for AM learning there should be. As an example, here are the learning outcomes from the course "3D design of a product" derived from the matrix: *"In the course, the student identifies different AM technologies and can define the AM principles. The student is able to compare different AM processes and distinguish them from each other and select the most suitable one for manufacturing considering polymer printing with practical exercises. The student understands the design principles of AM (DfAM) and can apply them in design work. The student understands the life-cycle and recycling of polymer products and is able to take them into consideration in the design work. The student can illustrate mechanical functions through 3D printing and understands the possibilities and limitations of the technology".*

Based on the experience of the main author, when the learning outcomes are described within the course, the different competence parts can be connected together in the description in order to make the learning outcome description more fluent. When the matrix shows a cross marked to a specific competence area, the required learning outcomes are selected to the course according to the level of the course. This means that all of the learning outcomes within the competence area are not always selected within one course. This description of the planned learning outcomes shows the result from the learning process when the student has completed the course with accepted grade. The detailed description of the learning outcomes within a course helps to recognize the acquired skills within the engineering degree when e.g. applying for a job.

## 7. Arranging AM education

The Lapland UAS 3D printing laboratory function leans to the usage of three different technologies, FDM, SLA and SLS. When the situation in the Nordic and Baltic countries is looked, these technologies present the most used AM technologies whereas plastics are the most used material (PLM Group, 2019). From educational point-of-view, a presentation of different AM applications is an important starting point for learning. According to PLM Group (2019), the most used application is using AM for prototyping (82%). The other applications (concept verification 65%, production tools 64%, end-use parts 41% and spare parts 32%) show the other areas where AM is used. Properties from each technology present possibilities for the student to learn and apply AM. The traditional AM process is based on the practical steps to be taken in order to print (3D modelling – STL conversion – slicing – machine setup – printing – removal – post processing) (Gibson et al., 2021). It can be stated that this basic AM process does not take the other views such as learning or selecting the most suitable AM technology into account. Therefore, more detailed model for the actual AM process selection is needed in order to specify the different learning aspects of the technologies and select the most suitable AM technology. According to 3D Hubs (2020), one way that fits well with engineering education, is to start the selection by dividing the AM applications into material, functionality and visual appearance as seen in Figures 3,4 and 5. All the materials and technologies have been limited into polymers and to the three technologies (FDM, SLA and SLS) mentioned in this study.

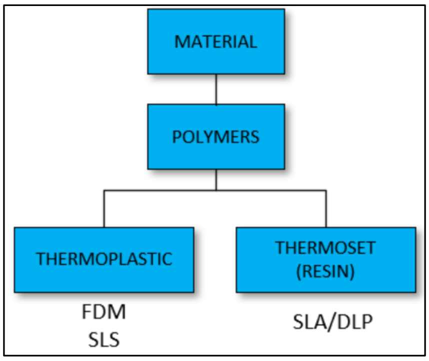


**Figure 3**: AM technology selection according to material
(Adopted from 3D Hubs, 2020)

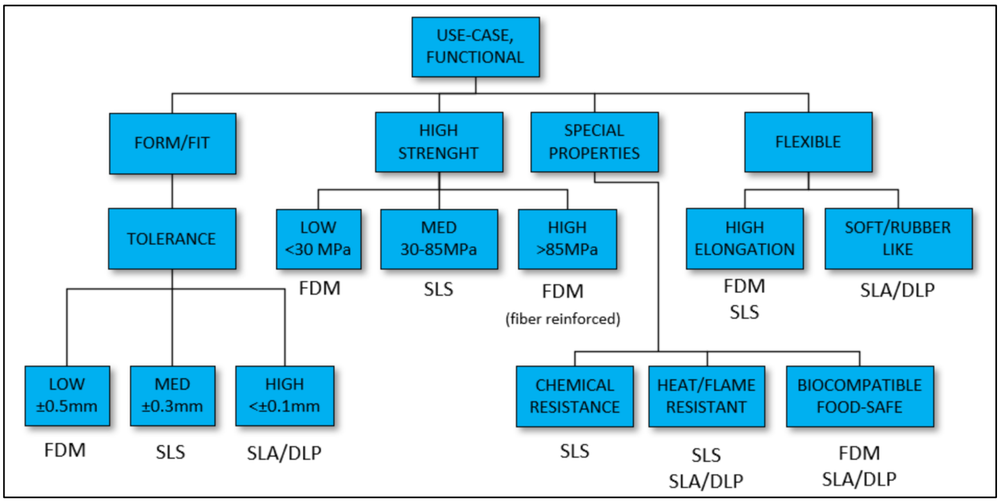


**Figure 4**: AM technology selection according to material
(Adopted from 3D Hubs, 2020)

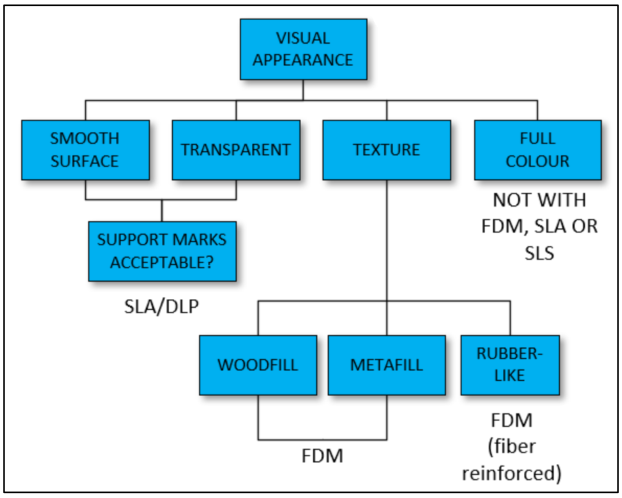


**Figure 5**: AM technology selection according to material
(Adopted from 3D Hubs, 2020)

Figures 3, 4 and 5 present three different ways to select the most suitable polymer printing technology. The selection requires the knowledge of the used material and the definition of the desired attributes. The specifications and demands of the design and build (e.g. accuracy) must be chosen and known (3D Hubs, 2020). Digital Light Processing (DLP) refers to one type of AM technology based also to photopolymerization such as SLA. DLP uses mask projection system to cure an entire layer at once where SLA uses laser and scanning galvanometer to cure layer point-wise (Gibson et al., 2021).

This division is used as a starting point in this study when more detailed selection of the correct printing process from a learning point of view is introduced. Figure 6 presents the detailed model for AM process selection.

As seen in Figure 6, the model presents a way to connect a traditional engineering design process with the basic idea of product development into AM process selection. The user designs the desired part with traditional design process principles (DfAM = Design for Additive Manufacturing principles included), which is usually based on a need. As a part of a product manufacturing process, 3D scanning can be used in this stage through reverse engineering. The physical 3D model is then analysed and possibly optimized through topology optimization and part consolidation. This stage enables the optimization of the structure and the preliminary definition of material properties. This already lays the ground for the actual AM process selection for manufacturing.

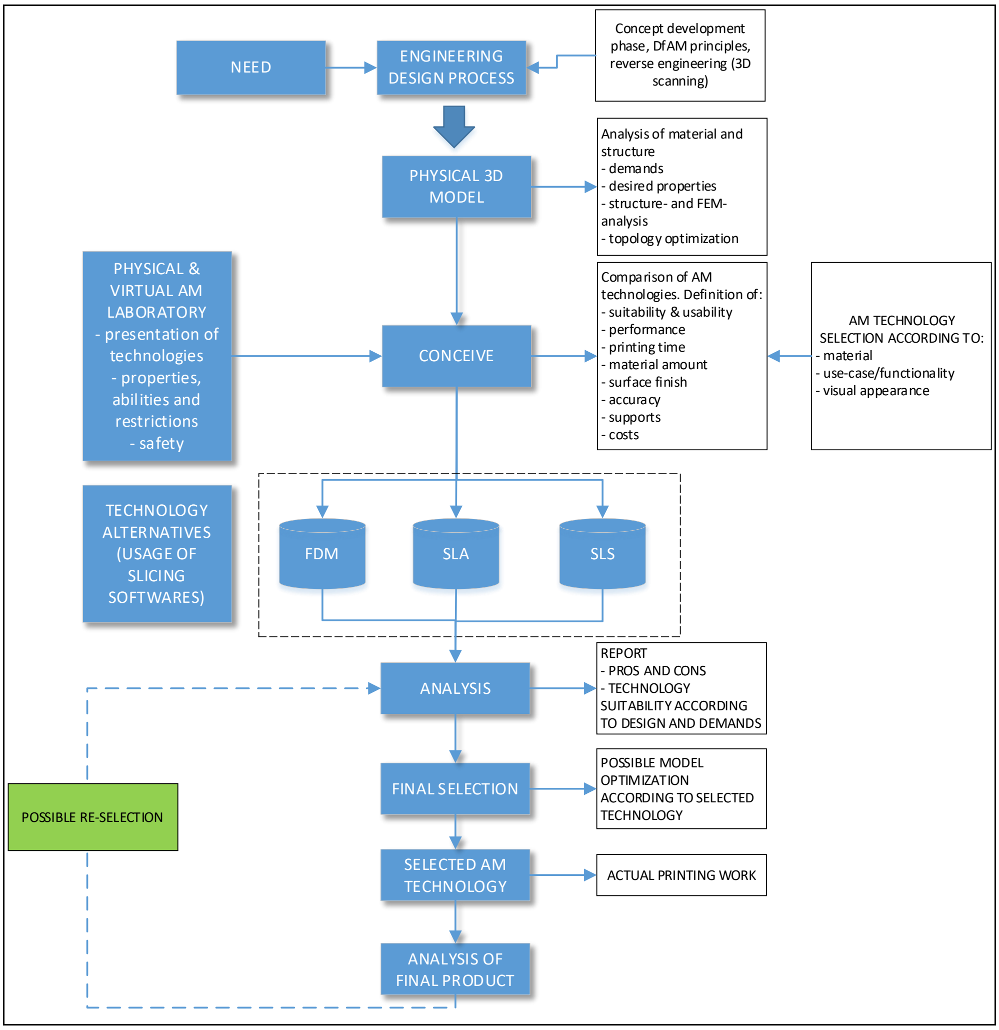


**Figure 6**: AM process selection model

In the conceive stage, the user is introduced to the laboratory environment first via virtual information tour. Before this, the student has already received necessary theoretical information about AM according to the curriculum. The virtual laboratory tour includes a 3D virtual model of the laboratory where the user can move around and introduce to embedded information about the printers. During the writing of this study, the virtualisation is at the planning stage and will be implemented later. After this, the practical introduction to the printers will be given in the laboratory (usage, safety, material loading etc.). These two stages give the user the required information about the laboratory in order to function there for learning purposes. At this stage, the possible technologies are reflected with the model according to different factors. This stage gives the user information for making the decision about the technology to be selected according to different criteria such as performance, accuracy. The basic AM process selection according to material, use-case/functionality or visual appearance is used at this stage. This stage includes studying the theoretical background about the technologies performed either before or during a certain course.

In the next stage, the user is introduced to the available technologies and comparison of the 3D printer connected slicing software. All the pros and cons of the technologies in relation to the 3D model are listed and the product demands are reflected with the technologies. This stage gives the user the final information for making the decision of the most suitable technology. When selecting the right technology, the user can still optimise the model if the technology has some special perspectives or demands in the manufacturing process. The manufactured part is analysed and if the result was not successful, the user return to the selection phase through iteration. This enables the quality of the manufactured part. The model can be used for learning purposes through selecting the most suitable AM process. The stages, where user has to acquire information or analyse a certain stage, enable the learning of different aspects of AM. Model is meant to be used in the beginning of the learning process and by using the most suitable AM technology, experience and knowledge increases. This creates a behaviour model for the user and when the process is familiar, the user can make the process selection with less phases.

## 8. Conclusion

The modern manufacturing industry is based mostly to traditional methods and additive manufacturing is on the verge of becoming recognized one of the reasonable alternatives for product manufacturing. In order to make this happen, the information about the possibilities of AM must be increased in the industry and companies. In order to increase the AM processes in the manufacturing industry, qualified machine operators are needed in addition to the AM knowledge. This sets requirements to engineering education and through proper arrangement of the AM education, it can produce necessary experts the work-life needs. Therefore, the development of curriculum and especially the detailed contents of AM courses are in focus. This requires the proper description of the required learning outcomes since it has to meet the demands set by the manufacturing industry. This can be divided into two different scenarios. In the first, the manufacturing industry is aware of the possibilities of AM and is using it in their functions. The industry and companies can direct the demands for AM skills and know-how to the engineering education. This way the engineering education can educate the professionals with the right AM knowhow. The other scenario is where the industry and companies are not using AM in their operations and are even lack information from AM. In this case, the function of the engineering education is to increase the awareness about the possibilities of AM through graduated engineers when they are employed. In this study, the questionnaire directed to the industry and companies in Finland presents that the situation is a hybrid of these. In either case, the engineering education must contain the proper skills for using AM as one alternative for manufacturing. Results from the conducted questionnaire can be formed as competence groups and within these, proper learning outcomes can be created which gives the pedagogical background to the required know-how from curriculum point-of-view. The competence matrix connects the competences with courses and this enables educators to plan the learning path along the whole degree so that the student can develop to become an AM expert.

The practical arrangement of AM education needs to be considered together with the pedagogical aspects. It is important for an engineering student to be able to select the most suitable AM technology for manufacturing. AM contains many factors that affect to the selection of the process and this study presents a model, how the selection between the most used AM technologies, FDM, SLA, SLS can be done. This model can be used with other technologies even if the technology (such as AM of metals) contains more specific aspects and demands for manufacturing. This model gives a substrate for using these more complex AM technologies as it presents a clear path for connecting AM technology into engineering design and to the features of the selected technology. The complete AM selection models, as presented in (3D Hubs, 2020), contain the AM technologies of metals. The versions used in this study have been adopted only to contain the selected three polymer AM technologies. The learning outcomes and AM process selection model will be used in future study where a group of Lapland UAS mechanical engineering students will study the basics of FDM, SLA and SLS technologies in a course. The student perspective will present the learning experiences between the technologies and present the learning threshold of each technology which will help in planning the actual usage of AM technologies in courses.

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**Appendix 1:** Responses from Basic Information

| | n | Percentage (out of n=56) |
|---|---|---|
| **1. The number of employees in the company?** | | |
| Less than 10 | 19 | 33.93% |
| 10 - 50 | 12 | 21.43% |
| 50 - 250 | 8 | 14.28% |
| Over 250 | 17 | 30.36% |
| **2. Does your company use 3D printing services?** | | |
| Yes | 31 | 55.36% |
| No | 25 | 44.64% |
| **3. 3D printing services used by the company** | | |
| Optimization of 3D models | 12 | 38.71% |
| Design of 3D printed parts | 15 | 48.39% |
| 3D printing work | 28 | 90.32% |
| Post processing | 17 | 54.84% |
| 3D scanning | 15 | 48.39% |
| Other (specify) | 1 | 3.23% |
| Other: | | |
| The simulation of the 3D printing process | | |
| **4. Does your company produce 3D printing services?** | | |
| Yes | 27 | 48.21% |
| No | 29 | 51.79% |
| **5. The 3D printing services produced by the company** | | |
| Design work | 21 | 77.78% |
| 3D printing work | 20 | 74.07% |
| 3D printer training | 11 | 40.74% |
| 3D printer sales | 5 | 18.52% |
| 3D scanning | 13 | 48.15% |
| Other (specify) | 7 | 25.93% |
| Other: | | |
| The simulation of the 3D printing process | | |
| Product development and optimization | | |
| Modeling | | |
| Fabrication of metal powder for 3D printing | | |
| Materials for 3D printing | | |
| Technical calculation and structural optimization | | |
| **6. Does your company need information about 3D printing** | | |
| **and its principles in the functions of the company?** | | |
| Yes | 31 | 55.36% |
| No | 25 | 44.64% |
| **7. Information needed about 3D printing** | | |
| Design principles in 3D printing | 24 | 77.42% |
| 3D printing technologies and materials | 25 | 80.65% |
| Possibilities provided by 3D printing for the company | 24 | 77.42% |
| Price factors in 3D printing | 22 | 70.97% |
| Other (specify) | 4 | 12.9% |
| Other: | | |
| General information about new 3D printing technolgies and materials | | |
| Details in 3D printing | | |
| The material models of printing materials for technical calculation | | |
| Continuous learning in each area | | |

**Appendix 2:** Numerical Results from Responses

| Scale | 0 - 6 | 7 - 8 | 9 - 10 | CNS | Mean value |
|---|---|---|---|---|---|
| **1. How important are the following topics in engineering education: Basics of 3D printing (technologies, principles, process)?** | 7 | 18 | 28 | 3 | 8.2 |
| | 13.21% | 33.96% | 52.83% | | |
| **2. The 3D printing of polymers and its possibilities.** | 9 | 24 | 21 | 2 | 7.7 |
| | 16.67% | 44.44% | 38.89% | | |
| **3. The 3D printing of metals and its possibilities.** | 5 | 20 | 29 | 2 | 8.4 |
| | 9.26% | 37.04% | 53.7% | | |
| **4. Knowledge of polymer materials in 3D printing** | 15 | 22 | 17 | 2 | 7.2 |
| | 27.78% | 40.74% | 31.48% | | |
| **5. Knowledge of metal materials in 3D printing** | 11 | 22 | 21 | 2 | 7.9 |
| | 20.37% | 40.74% | 38.89% | | |
| **6. Knowledge of composite materials in 3D printing** | 15 | 19 | 19 | 3 | 7.5 |
| | 28.3% | 35.85% | 35.85% | | |
| **7. Practical exercises in 3D printing of polymers** | 16 | 23 | 15 | 2 | 7.1 |
| | 29.63% | 42.59% | 27.78% | | |
| **8. Practical exercises in 3D printing of metals** | 17 | 20 | 17 | 2 | 7.4 |
| | 31.48% | 37.04% | 31.48% | | |
| **9. Design principles in 3D printing** | 4 | 15 | 34 | 3 | 8.8 |
| | 7.55% | 28.3% | 64.15% | | |
| **10. The optimization of 3D models (parts consolidation, topology optimization etc.)** | 9 | 12 | 32 | 3 | 8.3 |
| | 16.98% | 22.64% | 60.38% | | |
| **11. Possibilites to utilize 3D printing in the company functions** | 7 | 17 | 30 | 2 | 8.4 |
| | 12.96% | 31.48% | 55.56% | | |
| **12. Possibilites to utilize 3D printing in the industry** | 4 | 15 | 34 | 3 | 8.6 |
| | 7.55% | 28.3% | 64.15% | | |
| **13. The definition of viability of 3D printing in the product manufacturing process** | 6 | 20 | 27 | 3 | 8.4 |
| | 11.32% | 37.74% | 50.94% | | |
| **14. The common projects of engineering education and companies** | 13 | 26 | 14 | 3 | 7.3 |
| | 24.53% | 49.06% | 26.41% | | |
| **15. The recycling of 3D printed parts and materials** | 24 | 19 | 11 | 2 | 6.4 |
| | 44.44% | 35.19% | 20.37% | | |
| **16. Re-manufacturing of products through 3D printing (circular economy)** | 18 | 15 | 19 | 4 | 6.8 |
| | 34.61% | 28.85% | 36.54% | | |

# Publication V

Pikkarainen, A., Piili, H., and Salminen, A.
**Perspectives of mechanical engineering students to learning of additive manufacturing – learning through multiple technologies**

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# Perspectives of Mechanical Engineering Students to Learning of Additive Manufacturing - Learning through Multiple Technologies

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*Abstract* – **Additive manufacturing (AM) is a technology where an object is manufactured layer by layer based on 3D CAD data enabling new kind of freedom for design. AM is widely used especially in the universities and universities of applied sciences supporting the education of technical subjects which has increased the popularity of the technology. This has already led into new innovations in companies being able to benefit from the possibilities of AM when implementing AM in their processes. One of the most important issues in the use of AM in companies is the availability of experts able to adopt the AM principles e.g. to the manufacturing process. This requires the arrangement of diverse AM education by introducing multiple AM technologies to engineering students through perceived learning. Perceived learning combines the elements of situated learning and practice-oriented learning which were proved to be important elements in the arrangement of AM education in this study. This study presents a case study where student feedback and perceptions were collected and analysed regarding the use of multiple AM technologies simultaneously with relation to the learning results and to the development of their skill level and knowhow. The main goal of the study was to form a view about the use of multiple AM technologies simultaneously in engineering education and evaluate the development of students' AM expertise during the engineering studies. The study was based on an advanced 3D printing course for 6th semester mechanical engineering students of the Lapland University of Applied Science in Finland held in 2020. A questionnaire was conducted to the students targeting to map the learning experiences with multiple technologies. The study presents the importance of using multiple technologies simultaneously in AM education enabling advanced learning where the skill level and knowhow of the students increased better than with the use of just one AM technology at a time.**

*Keywords* – **Additive Manufacturing, 3D Printing, Higher Education, Learning, Engineering, Perceived Learning, Student Feedback, Multiple Technologies.**

## I. Introduction

Additive manufacturing (AM) is an emerging technology where physical objects are manufactured from 3D CAD data layer by layer giving new kind of freedom for design and manufacturing possibilities. The original purpose of the technology was mainly for prototyping purposes but the evolution of the technology has enabled the manufacturing of end-use parts and parts for tooling. One important factor has been the industrialization of AM where e.g. the aerospace industry introduced AM into their manufacturing process, for instance. The advantages, such as reduced lead times, freedom of design and pure simplicity of the complete manufacturing process accelerated the development of the technology (Diegel et al., 2019; EN ISO/ASTM52900, 2017; Niaki and Nonino, 2018).

The use of AM in education, especially in universities and universities of applied sciences, has been one factor in increasing the popularity of the technology. AM supports learning and innovation in education and has been noted to increase motivation towards technical subjects (Ford and Minshall, 2019). The research in universities has been a one source of innovations which has been developed into commercial actions and entrepreneurship (Ryan, 2020). As stated by Ford and Minshall (2019), AM is being used in many learning functions in universities, such as in project-based learning and laboratory work topics beside the traditional lecture type learning. This includes also AM related research activities where the universities perform traditional academic research and applied research in collaboration with the industry. According to the experience of the main author, the same can be seen in the university of applied sciences but more from the practical point of view. One of the main tasks of universities of applied sciences is to educate professionals according to the needs of work-life (Kangastie and Mastosaari, 2016). This emphasizes the role of applying engineering sciences and practical skills in the studies. Therefore, it can be said that the role of universities leans more to research whereas the role of universities of applied sciences leans toward applying engineering sciences and practical skills when discussing about the application of AM in education.

It has been noted by Yang (2018) that the project-based learning of AM in an effective way to learn the practical skills related to AM as the use of the technology required hands on manufacturing skills. These projects related practical circumstances enable the in-depth understanding and combination of knowledge into practice. Therefore, the traditional type of learning based on plain lecturing is not fully suitable for learning AM since it lacks the practical side of learning. The lecturer has to keep up-to-date information available for the students due to the fast development rate of AM and supports the interest and motivation of students' to learn AM. This shows the need to concentrate on the practical learning of AM e.g. in laboratories and learning environments related to AM and especially to the evaluation of the learning outcome from students' point of view. This study presents a case study from the Lapland University of Applied Sciences (Lapland UAS) in Finland where mechanical engineering students participated in 3D printing course containing multiple polymer printing technologies. This give a view to the practical learning of AM and to the students' own perception of the learning outcome through perceived learning and reflection. This is essential when evaluating the efficiency of AM education in engineering due to the demands set by the manufacturing industry related to AM. Achieving the best possible outcome for learning, the companies and industry are able to employ AM professionals who are aware about the possibilities and limitations to use AM in manufacturing processes.

Aim and purpose of this study is to view the perceptions and observations of mechanical engineering students at Lapland UAS when using multiple AM technologies of polymers from the learning point of view. The goal is to evaluate how the simultaneous use of FDM, SLA and SLS technologies increases the competence and knowhow a student in the area of additive manufacturing. This information can be used in the implementation of 3D printing courses at HEIs' (Higher Education Institutes), especially in the field of engineering (B.Sc. and M.Sc. levels).

## II. Theoretical Framework

The framework for this study concentrates on the learning factors behind AM and to the methods how the students can identify their own learning. The use of different learning methods and the analysis of learning based on these methods are in focus in this study. The literature background consists of learning methods connected with the practical side of learning due to the nature of AM education in engineering. Concepts of situated learning, practice-oriented learning, perceived learning and reflection form the theoretical background

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to this study as used learning methods.

Situated learning refers to the distribution and acquisition of knowledge in real settings and context as presented in Figure 1.

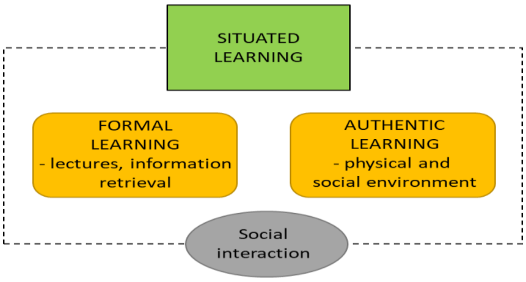


Fig. 1. Situated learning (Applied from Besar, 2018; Handley et al., 2007).

As seen in Figure 1, situated learning as a theory separates formal learning and authentic learning in a manner where formal learning happens in more traditional ways (knowledge acquisition e.g. through lecturing) while authentic learning happens within some physical and social environment (participation in real situation) (Besar, 2018). This is the strict way to view the theory and this study views situated learning as a part of the learning process; not the sole provider of information. Handley et al. (2007) states that knowing and learning are factors which are connected with situations in everyday life and must be researched together and cannot be separated. In addition, this includes the social interaction in the learning circumstances (e.g. at workplace or social situations) through individual interaction or interaction happening within a group. When looking at this study and the learning in 3D printing course, situated learning refers to embedding the learning process in the context of situations where the student experiences AM.

Practice-oriented learning aims to educate professionals according to the requirements set by the work-life based on flexible competence abilities. The modern society requires new kind of knowhow from the graduates who should be able to solve problems in a flexible way in different situations. Figure 2 presents the principle of the method.

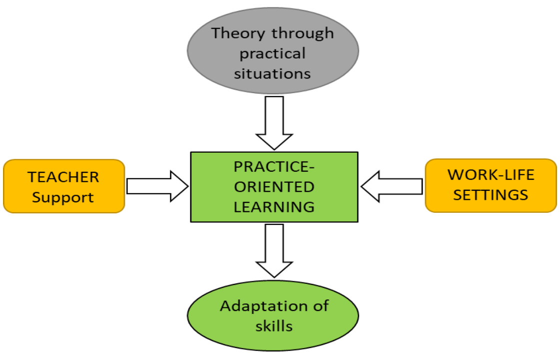


Fig. 2. Situated learning (applied from Smirnova et al., 2019; Chuchalin et al., 2014; Whelan et al., 2016; Abykanova et al., 2017).

As seen in Figure 2, this method is based on the application of theoretical information in practical circumstances. The teacher acts as enabler who supports the students' learning in real situations by giving support for using the theoretical knowledge in different events. This approach enables the adaptation of skills needed in work-life and enhances students' competence towards work-life through problem-solving (Smirnova et al., 2019). The professional aspect of the approach is important since the competitiveness in the labour market requires the education system to be reactive. Challenges such as globalisation, market demands and the need for skilled workforce require efficient educational infrastructure. This means that the graduates have to meet the requirements of the employers. Practice-oriented learning provides an answer how to face these challenges through conditions suitable for educating competitive professionals (Smirnova et al., 2019; Chuchalin et al., 2014; Whelan et al., 2016; Abykanova et al., 2017). When looking at the nature of AM education, it can be noted that majority of the learning happens through working with the AM machines performing the manufacturing process. It requires the combination on numerous variables such as design demands, material requirements and requirements coming from the use of the manufactured part.

When looking at the implementation of AM in the industry (e.g. aircraft or medical), it can be noted that the learning of AM in practical context within work life settings improves the competence of the graduates. As presented by Daniel et al. (2017), Oettmeier and Hofmann (2016) and Al-Ahmari et al. (2018), it can be noted that the use of AM either directly in the manufacturing process, supply chain or in the professional training of the work force, it will improve the quality of the work. When creating these same kinds of circumstances for AM education through practice-oriented learning, it leads to skilled personnel who are able to support the competitiveness in the manufacturing industry.

Perceived learning refers to the students' own perspective to learning and to the experience how the knowledge and skills are acquired. The principle of the method is presented in Figure 3.

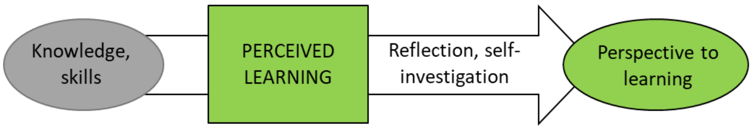


Fig. 3. Perceived learning (applied from Bacon, 2016; Zhang, 2016; Suhoyo, 2017; Moller and Shoshan, 2019).

As presented in Figure 3, the learning is usually measured through reflection and self-investigation from the learning. Perceived learning is often linked to the students' perception of teaching in a way where they evaluate how much they learnt e.g. from a course (Bacon, 2016). The measurement of the students´ learning is generally conducted through a feedback questionnaire (e.g. with Likert-scale with the scale of 1-5 where the number one represents "Disagree" and number five "Agree" options) as presented by Bacon (2016), Zhang (2016), Suhoyo et al. (2017) and Moller and Shoshan (2019). This study shows that investigating the nature of learning such as student expectations, pre and post situations of learning in a course, learning performance and evaluation of gained information, valuable information can be received especially to the development of the education. The mapping of the student experiences from learning is one main point in this study and this will be done through the evaluation of perceived learning.

These models are viewed together aiming to give information about the learning experience from using multiple AM technologies (including theoretical information and practical work with the AM machines). This study proposes that situation learning and practice-oriented learning can form the basis for perceived learning with AM as the context. The combination of these learning models is presented in Figure 4.

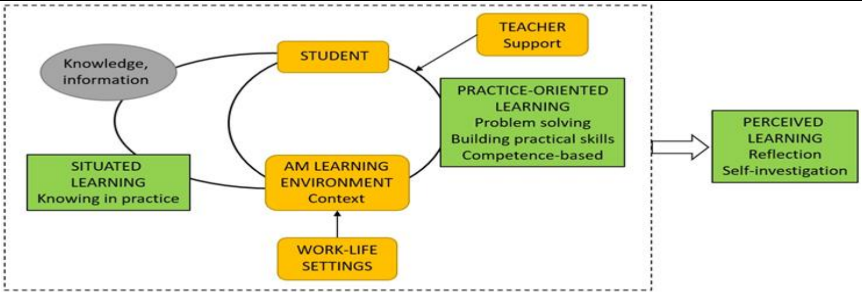


Fig. 4. Combination of the learning methods (applied from Besar, 2018; Handley et al., 2007; Smirnova et al., 2019; Chuchalin et al., 2014; Bacon, 2016).

As seen in Figure 4, by combining these three learning methods into the AM learning environment (AM learning environment presents the context in this study) broader view can be received from the learning. Situated learning happens within the context of the AM learning environment where the student can interact with other students and acquire knowledge guided and independently. Practice-oriented learning happens at the AM learning environment where the student applies theory in practice by solving problems and building practical skills needed in work life. The learning is competence-based and it reflects the contents of the engineering curriculum. The AM learning environment includes the settings from work life in a way which reflects the needs and requirements from work life. This leads to the perceived learning where the student reflects the learning outcomes by analysing a reporting what he/she learnt. The model seen in Figure 4 forms the theoretical framework for this study where the learning experiences of Lapland UAS mechanical engineering degree students are analysed when using multiple polymer AM technologies.

## III. Case Study - Arranging Additive Manufacturing Course

In spring 2020 an advanced course called "3D printing and applications" was held in the Lapland UAS mechanical engineering 3D printing laboratory. The main goal was to introduce the students to three polymer AM technologies: FDM, SLA and SLS. This happened through combining theoretical aspects and practical work. According to Statista (2020), these technologies present the three most used AM technologies at the moment and these are the technologies used in the Lapland UAS mechanical engineering 3D printing laboratory. The main point was to design an assembly which then would be printed by using the three technologies. The purpose was to combine the different technologies in manufacturing the assembly. This way the student was introduced to:

1. The detailed introduction of FDM, SLA and SLS technologies,
2. The comparison of the manufacturing capabilities and specifications of the three technologies,
3. Finding the best practices for the technologies based on the design work and
4. The learning of three technologies and comparing the learning thresholds.

The course, worth of 5 ECTS, started in January 2020 and the planned ending time was in May 2020. The course was an advanced course of AM provided as elective course for the 6th semester mechanical engineering students. The course was held for the first time, the number of participants was 16 and it utilized a new AM laboratory with 11 printers and three technologies (FDM, SLA and SLS). The Lapland UAS mechanical engineering curriculum contains the maximum of 20, 5 ECTS of AM studies (the students are able to learn theoretical information about FDM, SLA and SLS and perform practical studies from FDM) preceding this course giving the students a good background to a more advanced AM course with multiple technologies. The plan was to conduct a separate questionnaire for collecting feedback about the learning results of the technologies at the end of the course. The goal was to find out, how the learning of AM happens by using multiple technologies instead of one. Due to the COVID-19 situation, the Lapland UAS was closed in mid-spring and the nature of the course had to be changed. The course was changed to 100% distant learning making practical printing work impossible. The students introduced only to the theoretical aspects of the three technologies and implemented the design work. The groups continued the work on Fall 2020 when the Lapland UAS was again opened due to the improved situation of the pandemic in Finland. The work was continued in another course called “Future technology” with 2 ECTS of AM studies in Fall 2020 in order for the students to finish the printing work and achieve the desired learning outcome. These two courses are handled as one wholeness in this study and the collected experiences and feedback will be used in further development for the “3D printing and applications” course which is in focus in this study.

The learning outcomes used in this wholeness were drafted in earlier study which combined the needs and requirements of the industry and companies in Northern Finland area for the 3D printing education as presented in Figure 5.

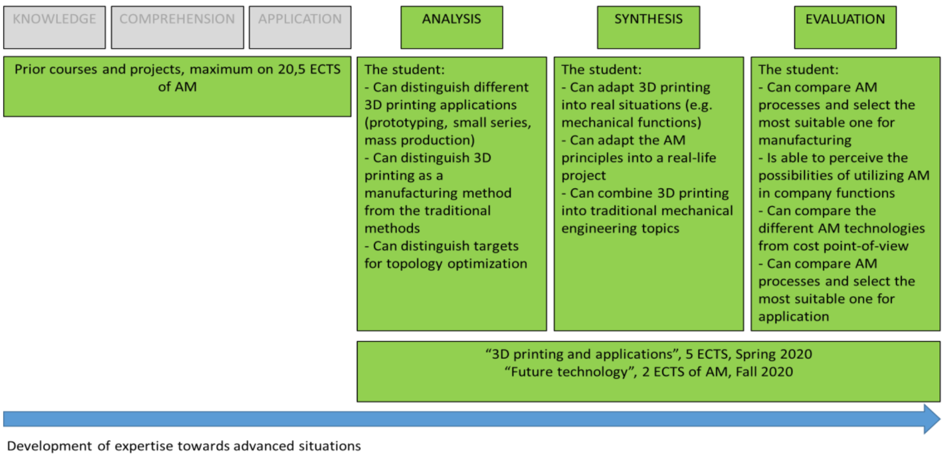


Fig. 5. Learning outcomes for the course and prior studies.

As seen in Figure 5, the categorization of the learning outcomes is based on the Blooms’ taxonomy dividing the outcomes into six categories according to their importance in the learning path: knowledge, comprehension, application, analysis, synthesis and evaluation. From this, the knowledge presents the beginning of the learning path; the student acquires information and recalls facts. In comprehension, the student presents an understanding about previously acquired information. In application, the student is able to use this information in new context. In analysis, the student investigates the information and analyses it. In synthesis, the student can derive new information from previous by compiling different areas together. In evaluation, the student is able to explain and justify the nature of the information and justify his/her own decisions and solutions (Bloom et al., 1956; Arapi et al., 2007; Meda and Swart, 2017; Stanny, 2016). The course “3D printing and applications” presents the more advances learning of 3D printing, therefore the learning outcomes are weighted on the latter part of the Blooms’ taxonomy (analysis, synthesis and evaluation). The learning outcomes have been drafted based on the requirements coming from work-life. The earlier parts of the path such as knowledge, comprehension and analysis have already been achieved in earlier semesters in different 3D printing courses and projects. This way it was ensured that the knowhow achieved by the student is up to date and based on work-life needs especially through more advanced learning situations. This improves the employment possibilities of the students and the distribution of information about the possibilities to use 3D printing in the industry and company functions.

The number of participants in the wholeness was 14 students and the amount of credits was 7 ECTS. Total amount of working hours related to AM for a student was 189 hours. From this, 69 hours was supervised (lectures and guided laboratories, partially distant) and 120 hours was reserved for the independent work of the students (design work, laboratory work and report writing). The wholeness was divided into theoretical and practical part as seen in Figure 6.

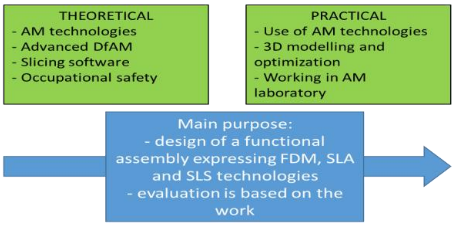


Fig. 6. Structure of the course contents.

As seen in Figure 6, the theoretical part introduced the student to the following topics:

1. 3D printing technologies of polymers: advanced information of FDM, SLA and SLS technologies and their possibilities.
2. Advanced information of DfAM (Design for Additive Manufacturing) principles.
3. Use of 3D printing slicing software (SLA and SLS).
4. The occupational safety of 3D printing laboratory with SLA and SLS (chemical safety, respiratory safety, risks and hazards).

The practical part of the course consisted of following topics:

1. The use of SLA (Formlabs FORM 3) and SLS (Sinterit LISA PRO) printers. FDM printing (Ultimaker S5, Prusa i3 MK3S and Creality Ender 3) had already been introduced in earlier semesters.
2. Design work: 3D modelling and optimization.
3. Working in 3D printing laboratory (the AM work phases, guided and independent work).

The evaluation of the course wholeness was based on the practical work done with course assignment. The main goal of the assignment was to introduce the students to the three used polymer printing technologies: FDM, SLA and SLS. The goal was to design a functional assembly based on DfAM principles. The students chose the topic for the work themselves and acquired approval from the teacher. The assembly had to manifest the possibilities and limitations of the used three polymer printing technologies either in individual parts or in the whole assembly.

The selection between the technologies was performed through a separate AM process selection as seen in Fig. 7.

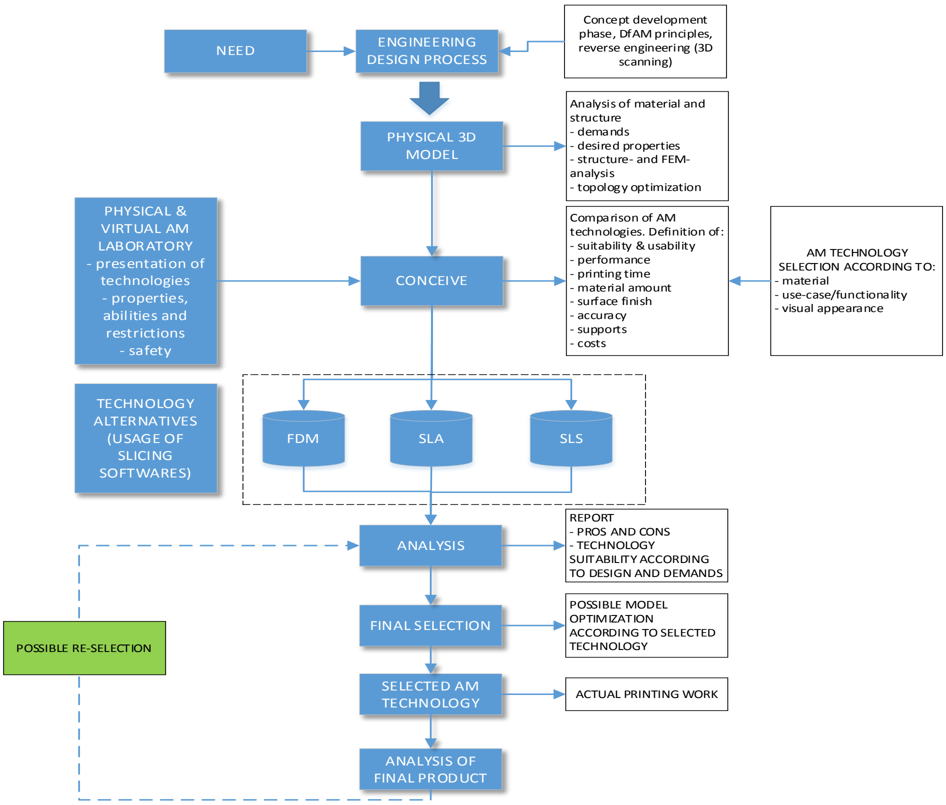


Fig. 7. AM process selection model (Pikkarainen et al., 2021).

As seen in Figure 7, the model enables the student to choose the most suitable polymer printing technology for each part. The goal is to familiarize the student to the selection work according to different criteria (material, accuracy visual appearance etc.). The selection is based on the traditional engineering design process enabling the phasing of the selection work. The model views the different factors related to the properties of AM parts. The model facilitates the selection especially in the beginning of the learning path when the experience level of the student is lower (Pikkarainen et al., 2021).

The first part of the design work was to print a prototype with FDM from each part and evaluate whether the result was good enough to be used in the final assembly. Requirements such as material, tolerance, strength and visual appearance set demands for the final result. From this, the students selected the parts to be printed with SLA and SLS, according to the AM process selection model. The process included all the necessary phases connected with each technology such as machine setup, print removal and post processing. As a final result, the students compared the SLA and SLS prints with the FDM prints based on these different factors. This way the students got the view to the properties and differences of these technologies, especially from the learning point of view.

Each technology presented different AM aspects and required a different kind of learning approach. The students wrote a report where they first addressed the theoretical aspects of each technology. They had to report the design work and actual printing work and analyse the final result from different perspectives such as equivalency to the original design, accuracy and visual appearance. The most important part of the analysis was to compare the different AM technologies from the technological and learning point of view. The goal of this analysis was to reflect the final result to the expected learning outcomes and learning process.

## IV. Methodology

This study presents findings from the analysis of students' experiences from using multiple 3D printing technologies in a 3D printing course wholeness "3D Printing and applications" and "Future technology" held in Lapland UAS in 2020. The presented data was collected anonymously through an electronical questionnaire (Webropol) consisting of numerical and written responses. The structure for the numerical questions is presented in Figure 8.

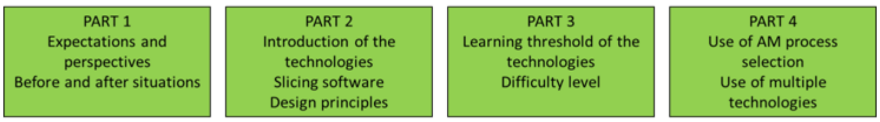


Fig. 8. Structure of the numerical questions.

As seen in Figure 8, the first section of the numerical questions was meant to map the students' opinions before and after the course regarding expectations and perspective of own knowledge and skill level. The numerical feedback was collected in Likert-style in the scale from zero to ten where zero presented the "minor", "failed", "weak" or "easy" option whereas number ten presented the "major", "successful", "strong" or "difficult" option. These explanations vary depending on the nature of the questions. The numerical questions together with the responses are presented in Appendix 1. The scale was selected for receiving more extensive dispersion in the responses. The responses from the first section would give an answer whether the course was successful and how it met the students' expectations. The second part of the numerical questions consisted of students' opinions about the technologies, use of slicing software and design principles. This would point out the students' opinions about the difficulty level of each technology. The third part of the numerical questionnaire dealt with the learning threshold of each technology. With this, the difficulty level of the introduction each technology could be mapped. The last section dealt with the use of the AM process selection model and the use of multiple technologies. The numerical questions are presented in Appendix 1. The numerical responses give information about the students' opinions from the course contents and AM topics from learning point of view. This helps in further development of the course and in the arrangement of 3D printing education especially with multiple technologies.

The responses to the written questions were collected and analysed in order to receive a view to the students' learning experience and to give the answer to the research questions presented in this study. Responses were collected with reflection and self-investigation questions from different learning topics connected with 3D printing. The written answers give a perspective to the students' observations of their learning process with multiple technologies based on the perceived learning approach. The nature of the written answers was analysed and conclusions were derived from the analysis. The list of the written questions is presented in Appendix 2.

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The written answers seek to give data from the learning experience regarding the use of three technologies and find possible places for improvement in the course.

The main hypothesis for this study was: Learning of 3D printing is more efficient when printing with multiple technologies. The research questions were derived from the hypothesis and the questionnaire was based on the questions. These questions were used as a foundation for the self-observation of a student. Research questions are as follows:

RQ1: How does learning process progress with multiple 3D printing technologies?

RQ2: What is the learning threshold of each technology (FDM, SLA and SLS)?

RQ3: What does each technology give to the learning of additive manufacturing?

RQ4: The analysis of the learning on one technology vs. multiple technologies; what kind of outcome gives the simultaneous learning and use of three technologies?

The structure of the study can be seen in Figure 9.

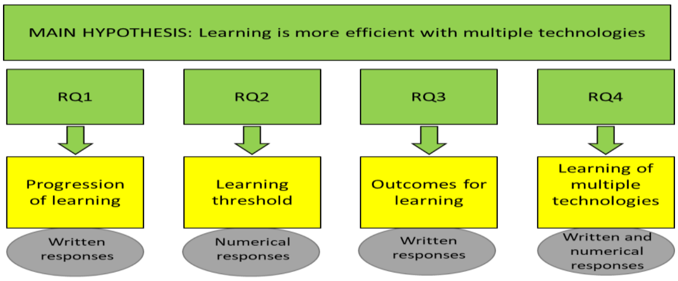


Fig. 9. Structure of the study.

As seen in Figure 9, the first topic concerned the progression of the learning process where written responses were used for the data analysis. This sets the foundation for this study by collecting the opinions from the students about the use of multiple technologies. For the evaluation of the learning threshold, the numerical scale was used. By presenting numerical questions from different topics related to the learning of each technology (e.g. the difficulty of use), the need for extra support for learning can be detected. The information about the different outcomes given by each technology was collected with written answers. The data was analysed by comparing the answers and picking information related to the nature of the technologies. The data from using multiple technologies simultaneously and the learning result was collected with numerical and written answers. This expressed the learning experiences of the students and gave direct answers.

## V. Results and Discussion

The student group size was 16 of which 14 answered the questionnaire resulting to the response rate of 87.5%. The numerical results were collected in a table presenting the percentages and average. The scale of the numerical questions was 0-10 and the responses can be seen in Appendix 1. The table shows each answer individually in order to get a better view, how the students view the areas of the questions. The following conclusions can be drawn from the numerical responses. Figure 10 presents the responses from the first part of the numerical questions concerning the expectations, perspectives and the before and after situations.

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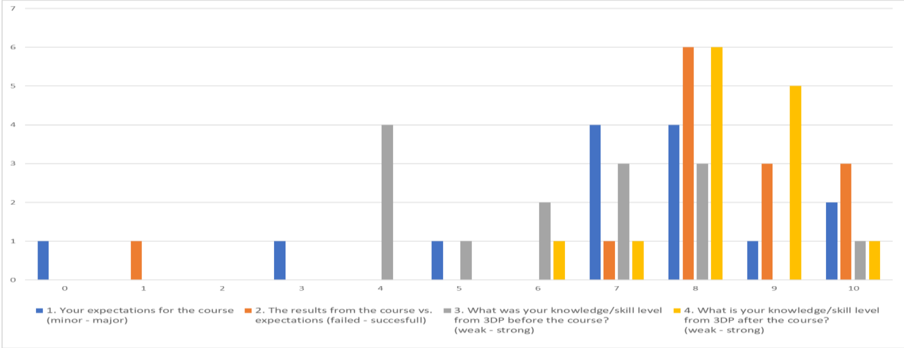


Fig. 10. Responses from part one of the numerical questions.

As seen in Figure 10, expectations were quite high as 3D printing is usually a quite popular topic in mechanical engineering. The amount of higher responses regarding the expectations vs. results grew indicating that the students felt that the expectations were met. The course was arranged for the first time and these results indicate that the direction of the course contents was correct and the development of the course can continue based on these results. The knowledge and skill levels at the beginning of the course were based on previous studies and courses which contained theoretical basics from SLA and SLS. FDM was introduced already in detail theoretically and practically in previous courses. The results show that the students´ knowledge and skill level increased during the course. The responses especially in the upper scale increased compared with the situation before the course. Figure 11 presents the responses from the second part of the numerical questions concerning the introduction of the technologies, use of slicing software and the application of design principles.

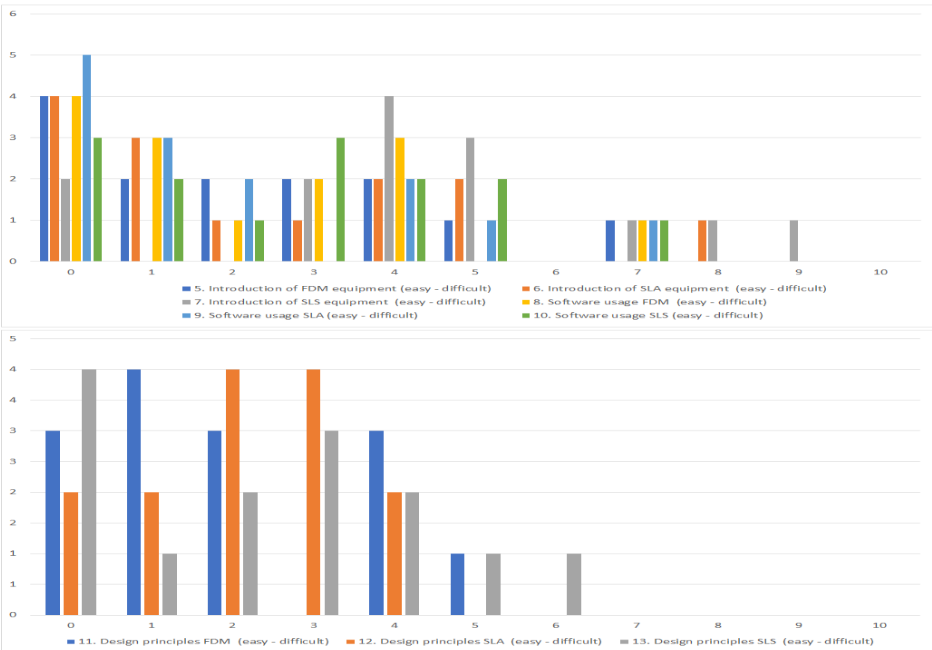


Fig. 11. Responses from part two of the numerical questions.

As seen from Figure 11, FDM (introduction, use and slicing software) was regarded easy to handle. This can be explained based on the students' experience from previous studies and courses. SLA was introduced in practise for the first time in this course but due to the easiness of FORM3 use, the students felt that the introduction was relatively easy. The numerical differences in the responses compared with FDM are quite narrow which shows that SLA suits well for educational purposes. This is a good indication that SLA could be introduced right after FDM or even when planning the timeframe for introducing different AM technologies to engineering students. SLS was introduced in practise for the first time in this course and the students felt that it presented to be more difficult than FDM and SLA. This can be explained by the nature of powder bed fusion equipment and the process; the start-up of process requires more time and work phases especially in the powder handling. SLS require the most theoretical information for using the process and to understand the behaviour of the material. This indicates that SLS should be the last technology to be introduced from these three as it presented to be the most demanding and challenging. SLA and SLS software use experiences were similar and regarded more difficult than in FDM. This can be explained by the fact that the students have more experience in FDM slicing software compared to SLA or SLS. Responses from the design principles from three technologies were similar and they were viewed as relatively easy. This can be explained by the fact that the AM design principles have already been learnt in previous courses and the Lapland UAS mechanical engineering students have many courses addressing engineering design and 3D CAD design. The students are able to realise the demand for design work in engineering and are able to distinguish the traditional engineering design principles from DfAM (Design for Additive Manufacturing). This indicates the importance of learning engineering design principles before or beside AM. The responses from the third part concerning the learning threshold and difficulty level of the technologies is presented in Figure 12.

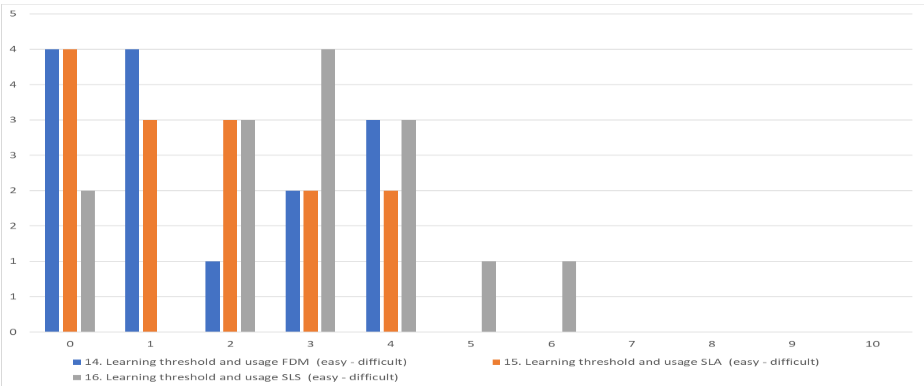


Fig. 12. Responses from part three of the numerical questions.

As seen in Figure 12, the learning threshold of FDM was seen relatively easy. SLA presented similar responses than FDM but it was regarded more difficult. The nature of SLA technology brings demands of a new kind due to the reverse orientation of the part in the build platform and used material (liquid resin). This leads to different design demands that the students have used to. The part must be printed usually in an angle due to the cross-sectional forces during print. This demands more from the support structure design and although the slicing software produces the support automatically, the user has to know more if the supports will be edited in order to achieve better surface finish in desired areas.

SLS presented more dispersion in the responses regarding the learning threshold but was regarded the most difficult from these three technologies. The nature of the powder causes challenges due to the small particle size making it sensitive to electrostatic forces and dispersion to air causing it to float to surfaces. This requires attention and consideration in the powder feeding phase in order achieve a print-ready state for the equipment. Due to the nature of the printing process (powder feeding, preheating, printing time, powder cooling and removal), SLS demands the most time from these three technologies. The students faced some challenges concerning time use and planning which indicate that this must be emphasized when SLS is introduced to the students. This is due to the fact that SLS is the demanding technology from these three and therefore should be used in the latter semesters of engineering studies. The students experienced the freedom for the design due to the unnecessary support structures. In SLS, the supports structures are not needed normally due to the self-support properties of the powder-like material. The optimization of part places and orientation in the powder bed was considered challenging. This is due to the heat distribution caused by the laser when manufacturing progresses layer by layer causing possible anisotropy and particle sticking if the orientation or placement is done without proper consideration. The most important issue to be considered are the heat zones in the printing bed together with the proper part orientation. Depending on the printer type, there is the so-called “safe zone” in the powder bed which presents an area the user can freely use without worrying the heat distribution. This area is in the centre of the bed. As we move away from the bed centre, the powder cooling changes leading to possible problems in the print. The further you move from the centre, the more unreliable the result will be. The slicing software (such as the Sinterit Studio used in the SLS printer presented in this study) present this as areas (usually green area = safe zone, yellow area = risk zone, red area = failure zone). In addition, radical change in the cross-section area between layers must be avoided due to the heat distribution; this can cause stress and distortion in the part. This requires the most investigation about the theoretical issues behind SLS which is a good example of the importance of situated learning and knowledge retrieval before the actual practice-oriented learning.

This shows that SLS in the most demanding of these three and requires more time and effort to learn. This emphasizes the importance of course planning when sufficient amount of time must be reserved for the introduction of each technology, especially with SLS which was considered the most time-consuming when looking from learning point of view. Figure 13 presents the final part of the numerical responses regarding the use of AM process selection model and multiple technologies.

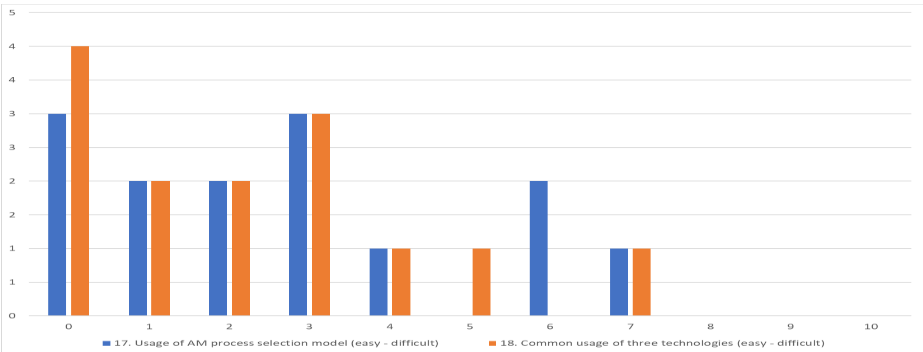


Fig. 13. Responses from part four of the numerical questions.

As seen in Figure 13, the AM process selection model was seen to be relatively easy to use. More comments about this are included in the analysis of the written answers. The responses show that the students did not feel that the use of three technologies simultaneously insurmountable. The majority of the responses were in the lower scale (0-5) which indicates that the students respond well to the use of multiple technologies in the same course.

The written answers gave broad feedback presenting the opinions and perceptions of the students about the learning of AM. The following presents a collection of the answers together with analysis. If the answers presented similarity in nature, they would be presented in same manner. Regarding the use of multiple AM technologies simultaneously, the largest common factor in the responses were the possibility to compare the results between three technologies. The students reflected e.g. the surface quality and accuracy between the print results which helped them to select the most suitable printing technology for application. In addition, the students learned the differences better between the different technologies and learning with multiple technologies was seen as an excellent learning method concerning AM.

*"It is interesting when you can compare the results between the technologies regarding surface quality and accuracy"*

*"Excellent learning method! You can learn and experience the three technologies at the same time and compare the result better"*

Other noticeable issue was the material knowledge and behaviour issues. The students realised the importance of knowing the properties of the materials which is essential when using polymer materials with different technologies. Last, the students noticed that the use of different technologies gave more freedom to the work, especially if the parts for the assembly were printed with different technologies. This led to better understanding about the application and possibilities of each technology.

*"The use of three technologies is relatively easy. The knowledge about materials plays important role. The behaviour of different materials must be known or else the result will fail"*

*"The use of multiple technologies gives more freedom"*

*"When printing an assembly with multiple technologies, it gives more freedom e.g. through material selection and possibilities"*

When the outcome for learning AM through multiple AM technologies was asked, all students felt that the use of three technologies strengthens the learning outcome. The students were able to compare the results immediately and map the strengths and weaknesses of each technology. It gave a wider perspective to AM especially when selecting the most suitable technology. The students were able to realise that SLS requires multiple prints at the same time due to process principles promoting several parts at-a-time production compared with FDM, which is fast method for individual parts according to Gibson et al. (2021).

*"The use of multiple technologies simultaneously helps to identify the strengths and weaknesses and gives broader perspective to additive manufacturing"*

*"FDM is ideal when printing a single part but SLS requires the printing of multiple parts due to the longest required time for the process"*

The majority of the students felt that their AM skills developed well during the course. This was supported most commonly in the responses by the development of AM process selection skills, the students were able to compare the processes better and through it, their AM skills improved. In addition, the motivation towards the utilization of AM increased as the students realised the development of their own skills.

*"I experienced a great leap in the development of my own know-how"*

*"The usage of multiple AM technologies improved my skill level greatly, I learned to select the most suitable AM process in order to achieve successful result"*

Concerning the AM process selection model, the majority of the students responded that the model was comprehensive and helped especially in that case when the technologies were not so familiar. The model was considered useful especially concerning the selection through tolerances and surface quality which supports the student in the early phase of AM learning with less experience. The model was seen as a good aid when printing assemblies and comparing which technology would be suitable. The model is especially helpful when parts for an assembly are printed with different technologies. Factors such as tolerance and fit are essential in the assembly work and the AM process selection model help the student in selecting the most suitable technology. Three out of 14 responses said that the model was not helpful in the selection since it diminishes the accuracy capabilities of FDM and even might confuse the selection as the selection should be done according to material properties and requirements of use. This might be explained that some of the students already have good experience from AM and therefore the AM process selection model is not that significant for them. In addition, part of these three answers reveal that the students did not investigate the model accurately as they stated issues to be missing that indeed were included in the model.

*"The model helped me to conceive which technology is suitable to certain occasion or application"*

*"The AM process selection model helped especially when considering the tolerance and shape requirements of the design"*

*"The model confuses the selection since the printing process should be selected according to material properties and the purpose of use"*

When asking what does each technology give to the learning of AM, the students identified the features of each technology well. The students were able to detect and learn differences such as in slicing software, printing methods and the process, design principles, the use of support materials and last, the differences in post-processing. The students felt that through the use of multiple technologies, their knowhow became more versatile.

*"The usage of multiple AM technologies made my knowhow more versatile"*

*"This showed that FDM is not the only AM technology and every technology has its strengths and weaknesses"*

Concerning the difficulties in using and learning different technologies, the students felt that FDM did not present any difficulties since it was familiar to them already from previous courses and some students practise FDM printing at their home, for instance. In SLA, the students felt that the printing process has quite many phases and the most difficult was to remember the correct order of the printing process (material loading and setup, removal, IPA washing etc). In addition, the use of support materials in a right manner in SLA was more difficult than in FDM or SLS. SLS presented to be the most challenging due to the complex nature of the powder handling in different phases. The students felt that the learning of SLS took the longest time, which is a good indication for a future course arrangement to give more time to the practical side of SLS. In addition, the optimization of parts in SLS in the powder bed was regarded more difficult even though the slicing software performs the part insertion automatically. The used software, Sinterit Studio, performs the nesting and orientation of the parts automatically. The fine tuning of the print job in powder bed requires expertise (when considering heat distribution, part orientation and printing time) and it is an issue at the beginning of the SLS learning path that requires time and concentration.

*"FDM did not present any challenges since it was already familiar to me"*

*"SLA presented to be multiphase AM technology and remembering the correct order of the phases was challenging"*

*"SLS was personally the most difficult for me, one issue was the amount of required time for use"*

Last, the students had the opportunity to give free feedback about the course and topics. The students would like to have more teaching from the AM materials which is a good point for improvement for the theoretical courses. In addition, the students noticed that the printing requires quite a lot of time and this issue was already solved by giving the students access to the 3D printing laboratory so that they are able to work outside the official lectures. This requires active independent work and motivation from the student outside the lectures. Altogether, the course got really positive feedback from the students who felt that it gave them a lot of new information about AM. The COVID-19 situation left a mark to the learning process but the student realised this and were aware of the limitations the situation brought to the lectures.

*"The use of time for the printing work must be planned carefully"*

*"The course was very educational and interesting. It was nice that you could use your own imagination with the printing work"*

*"The topic is relatively new and becoming more and more popular. It is important to learn AM since it will be more and more connected to the work of engineers"*

## VI. Conclusion

This study was conducted in order to map the learning experiences of engineering students when printing with multiple AM technologies in Lapland UAS mechanical engineering degree. In many cases, the current literature presents only one AM technology being used in e.g. in engineering courses and there is lack of research data from using multiple technologies especially when looking the result from a learning point of view. By using multiple AM technologies, when the learning is based on the requirements from work-life, the students are able to develop into experts and therefore improve their employment options. The companies can benefit from the AM expertise the graduated engineers possess and receive information about the possibilities of AM for their functions and processes. This improves the profitability and competitiveness of the companies as they are able to adopt the principles to their operations.

The analysis of the students' learning experiences was based on a questionnaire where the numerical and

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written responses presented in this study were analysed when forming the main conclusions. FDM was considered to be the easiest to learn and the students felt that FDM gave them good understanding and readiness to use AM in different learning cases. This presents that FDM supports students at the beginning when looking at the AM learning path towards more demanding technologies. SLA and SLS present more challenges due the nature of the technologies being more demanding than in FDM. Concerning SLA, issues such as support structure design and the number of process phases were seen challenging. The students felt that despite the challenges, the technology was easy to use and produced excellent accuracy and quality. Based on the numerical responses to the questionnaire, SLA was considered narrowly to be more difficult to learn and use than FDM. Concerning SLS, issues such as powder handling and working time were seen challenging and the technology was seen the most difficult to learn and adopt from the three technologies presented in this study. The students usually reflect these experiences in the use of FDM which is relatively easy and a fast way to produce e.g. prototypes.

Using multiple technologies in an AM course leads to increased motivation and skill level from AM based on the results from this study. The students are able to compare different technologies and select the most suitable AM technology through testing the features such as accuracy, surface quality and material properties in practical circumstances. By using the AM process selection model, the students are able to facilitate the process selection especially at the beginning of the learning path therefore supporting the student in learning. When using these three technologies simultaneously (FDM, SLA and SLS), it can be noted that the learning becomes more efficient since the students can compare the results immediately and therefore analyse and reflect factors such as design principles and material selection to the end result. The skill level of the students becomes more versatile than with just one technology and they are able to realise the possibilities of each technology better.

The future development of AM education requires the development of AM learning environments containing up-to-date AM equipment and the possibility for students to use them independently after they have sufficient knowledge about the technologies (theoretical and practical) through situated and practice-oriented learning. This requires new kind of view to engineering education where traditional classroom lecturing is replaced with versatile learning where the student is able to reflect, research and analyse his/her own learning through perceived learning. Graduated engineers must possess sufficient AM skills in order to export information to companies about the possibilities to use AM in their operations. This requires versatile AM courses where the students can learn and experience AM with multiple technologies simultaneously. This enables more advanced learning situations with AM enabling the student to develop into experts according to the needs and requirements set by work-life.

## VI. APPENDIXES

Appendix 1. Numerical questions and responses.

| | Scale | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Your expectations for the course | Minor-Major | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 4 | 4 | 1 | 2 |
| | | 7.15% | 0% | 0% | 7.14% | 0% | 7.14% | 0% | 28.57% | 28.57% | 7.14% | 14.29% |
| 2. The results from the course vs. expectations | Falled-Succesfull | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 6 | 3 | 3 |
| | | 0% | 7.14% | 0% | 0% | 0% | 0% | 0% | 7.14% | 42.86% | 21.43% | 21.43% |

| | Scale | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3. What was your knowledge/skill level from 3DP before the course? | Weak-Strong | 0 | 0 | 0 | 0 | 4 | 1 | 2 | 3 | 3 | 0 | 1 |
| | | 0% | 0% | 0% | 0% | 28.57% | 7.14% | 14.29% | 21.43% | 21.43% | 0% | 7.14% |
| 4. What is your knowledge/skill level from 3DP after the course? | Weak-Strong | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 6 | 5 | 1 |
| | | 0% | 0% | 0% | 0% | 0% | 0% | 7.14% | 7.14% | 42.86% | 35.72% | 7.14% |
| 5. Introduction of FDM equipment | Easy-Difficult | 4 | 2 | 2 | 2 | 2 | 1 | 0 | 1 | 0 | 0 | 0 |
| | | 28.57% | 14.28% | 14.29% | 14.29% | 14.29% | 7.14% | 0% | 7.14% | 0% | 0% | 0% |
| 6. Introduction of SLA equipment | Easy-Difficult | 4 | 3 | 1 | 1 | 2 | 2 | 0 | 0 | 1 | 0 | 0 |
| | | 28.57% | 21.43% | 7.14% | 7.14% | 14.29% | 14.29% | 0% | 0% | 7.14% | 0% | 0% |
| 7. Introduction of SLS equipment | Easy-Difficult | 2 | 0 | 0 | 2 | 4 | 3 | 0 | 1 | 1 | 1 | 0 |
| | | 14.29% | 0% | 0% | 14.29% | 28.57% | 21.43% | 0% | 7.14% | 7.14% | 7.14% | 0% |
| 8. Software usage FDM (CURA) | Easy-Difficult | 4 | 3 | 1 | 2 | 3 | 0 | 0 | 1 | 0 | 0 | 0 |
| | | 28.57% | 21.43% | 7.14% | 14.29% | 21.43% | 0% | 0% | 7.14% | 0% | 0% | 0% |
| 9. Software usage SLA (PreFORM) | Easy-Difficult | 5 | 3 | 2 | 0 | 2 | 1 | 0 | 1 | 0 | 0 | 0 |
| | | 35.71% | 21.43% | 14.29% | 0% | 14.29% | 7.14% | 0% | 7.14% | 0% | 0% | 0% |
| 10. Software usage SLS (Sinterit Studio) | Easy-Difficult | 3 | 2 | 1 | 3 | 2 | 2 | 0 | 1 | 0 | 0 | 0 |
| | | 21.43% | 14.28% | 7.14% | 21.43% | 14.29% | 14.29% | 0% | 7.14 | 0% | 0% | 0% |
| 11. Design principles FDM | Easy-Difficult | 3 | 4 | 3 | 0 | 3 | 1 | 0 | 0 | 0 | 0 | 0 |
| | | 21.43% | 28.57% | 21.43% | 0% | 21.43% | 7.14% | 0% | 0% | 0% | 0% | 0% |
| 12. Design principles SLA | Easy-Difficult | 2 | 2 | 4 | 4 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 14.28% | 14.29% | 28.57% | 28.57% | 14.29% | 0% | 0% | 0% | 0% | 0% | 0% |
| 13. Design principles SLS | Easy-Difficult | 4 | 1 | 2 | 3 | 2 | 1 | 1 | 0 | 0 | 0 | 0 |
| | | 28.57% | 7.14% | 14.29% | 21.43% | 14.29% | 7.14% | 7.14% | 0% | 0% | 0% | 0% |
| 14. Learning threshold and usage FDM | Easy-Difficult | 4 | 4 | 1 | 2 | 3 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 28.57% | 28.57% | 7.14% | 14.29% | 21.43% | 0% | 0% | 0% | 0% | 0% | 0% |
| 15. Learning threshold and usage SLA | Easy-Difficult | 4 | 3 | 3 | 2 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 28.57% | 21.43% | 21.43% | 14.28% | 14.29% | 0% | 0% | 0% | 0% | 0% | 0% |
| 16. Learning threshold and usage SLS | Easy-Difficult | 2 | 0 | 3 | 4 | 3 | 1 | 1 | 0 | 0 | 0 | 0 |
| | | 14.29% | 0% | 21.43% | 28.57% | 21.43% | 7.14% | 7.14% | 0% | 0% | 0% | 0% |
| 17. Usage of AM process selection model | Easy-Difficult | 3 | 2 | 2 | 3 | 1 | 0 | 2 | 1 | 0 | 0 | 0 |
| | | 21.43% | 14.28% | 14.29% | 21.43% | 7.14% | 0% | 14.29% | 7.14% | 0% | 0% | 0% |
| 18. Common usage of three technologies vs. the usage of just one | Easy-Difficult | 4 | 2 | 2 | 3 | 1 | 1 | 0 | 1 | 0 | 0 | 0 |
| | | 28.57% | 14.29% | 14.29% | 21.43% | 7.14% | 7.14% | 0% | 7.14% | 0% | 0% | 0% |

Appendix 2. Free form questions.

| Written Questions | Free form Answer |
|---|---|
| 1. What is your experience using multiple 3D printing technologies simultaneously? | |
| 2. Does the simultaneous usage of multiple 3DP technologies strenghter/weaken the learning of 3DP? Justify your answer. | |
| 3. How did you feel the development of your skills during the course (Learning process)? | |
| 4. Did the AM process selection model help you in selecting the suitable technology for printing? (How? Possible) | |
| 5. What different each technology (FDM, SLA, SLS) gave to the learning of 3D printing? | |
| 6. What was the most difficult thing in learning and using the technologies (name according to each technology)? | |
| 7. Suggestions for improving the course? | |
| 8. Free word and general opinions | |

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