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

Ari Pikkarainen [1*], Heidi Piili [2] and Antti Salminen [3]

[1] Senior Lecturer, Mechanical Engineering, Lapland University of Applied Sciences, Kemi, Finland.
[2] Professor, Research Group of Laser Materials Processing and Additive Manufacturing LUT School of Energy Systems, LUT University, Lappeenranta, Finland.
[3] Professor, Department of Mechanical and Materials engineering, University of Turku, Turku, Finland.
*Corresponding author email id: ari.pikkarainen@lapinamk.fi

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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 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.

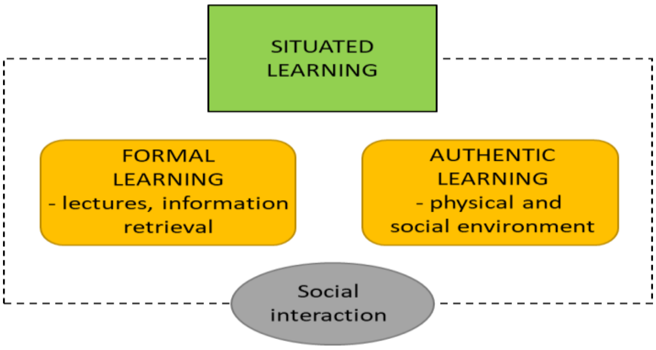

Fig. 1. Situated learning (Applied from Besar, 2018; Handley et al., 2007).

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.

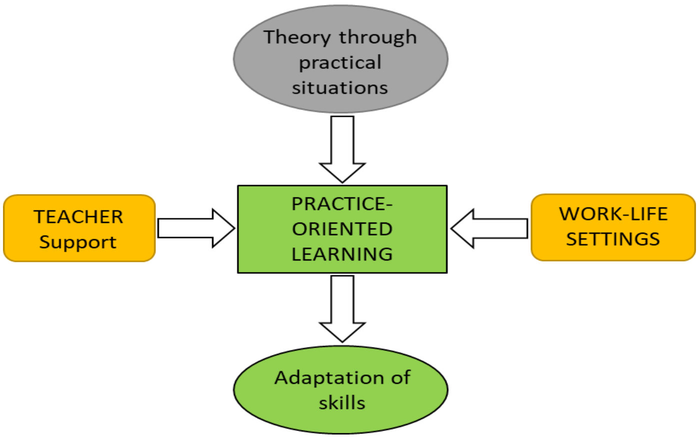

Fig. 2. Situated learning (applied from Smirnova et al., 2019; Chuchalin et al., 2014; Whelan et al., 2016; Abykanova et al., 2017).

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.

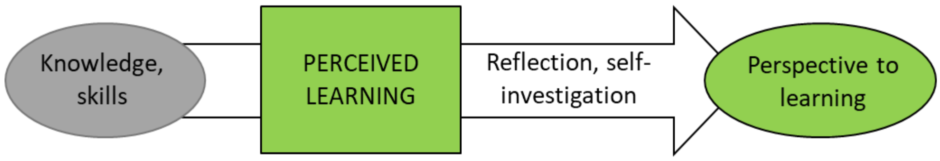

Fig. 3. Perceived learning (applied from Bacon, 2016; Zhang, 2016; Suhoyo, 2017; Moller and Shoshan, 2019).

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.

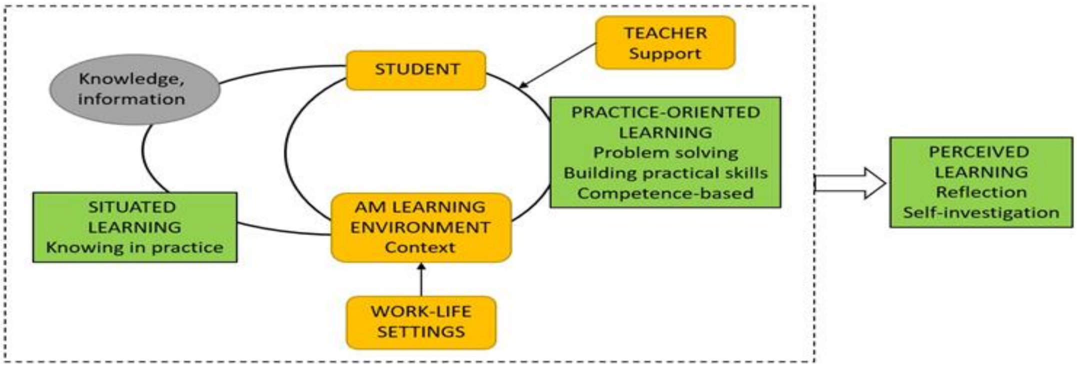

Fig. 4. Combination of the learning methods (applied from Besar, 2018; Handley et al., 2007; Smirnova et al., 2019; Chuchalin et al., 2014; Bacon, 2016).

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.

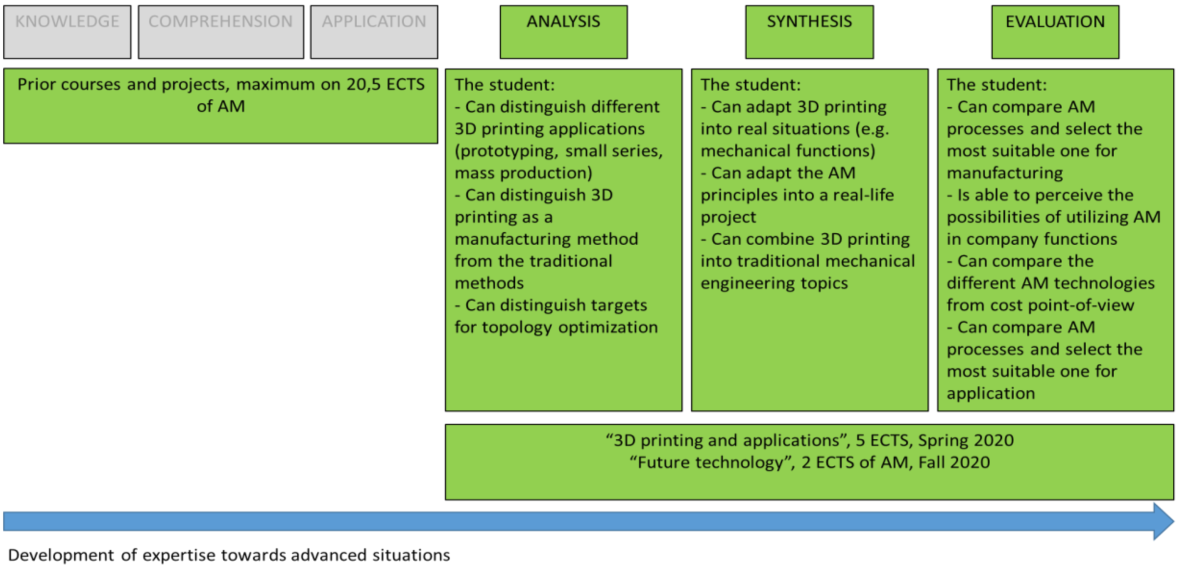

Fig. 5. Learning outcomes for the course and prior studies.

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'

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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.

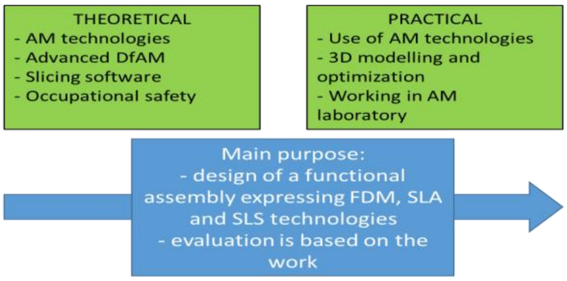

Fig. 6. Structure of the course contents.

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.

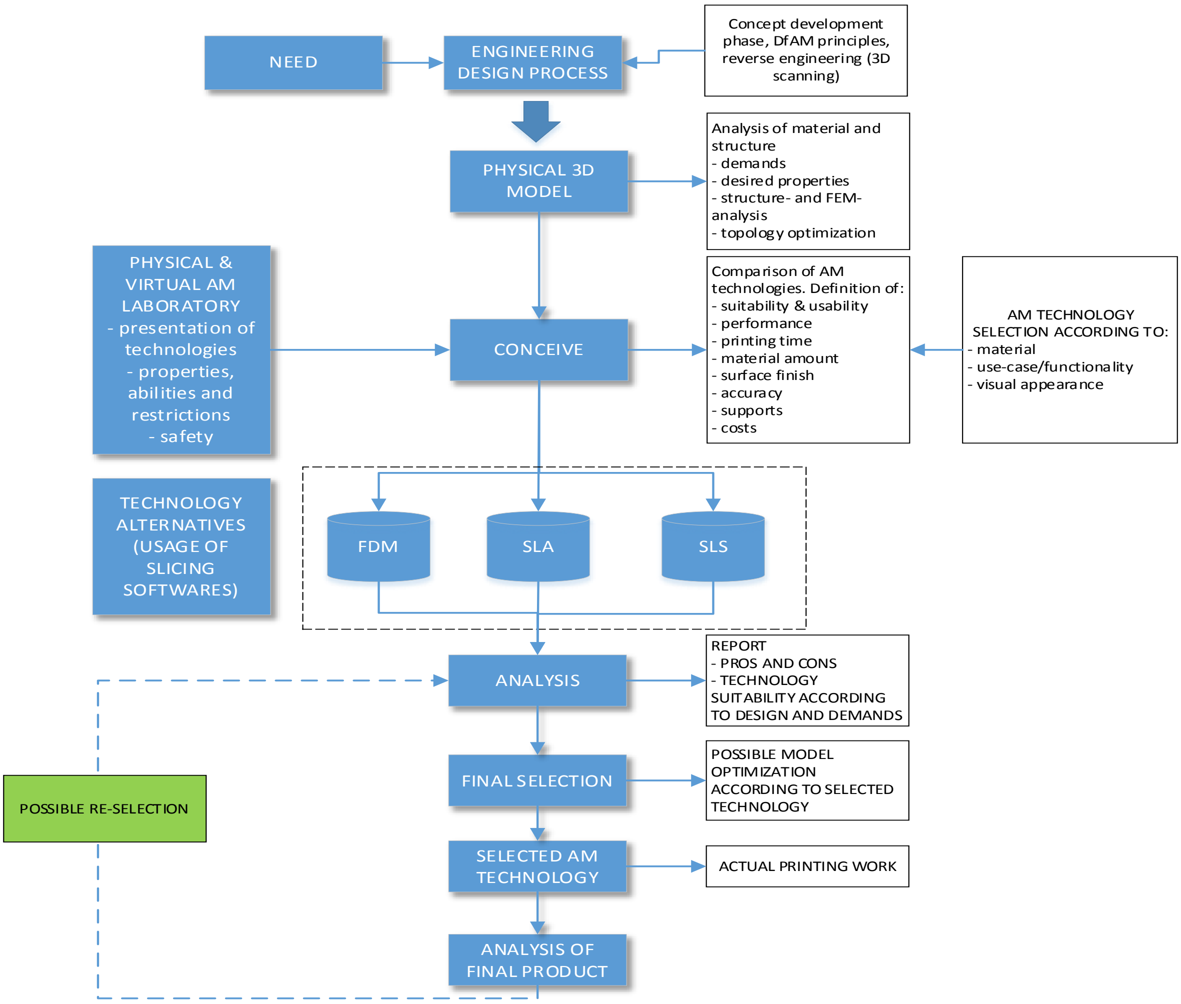

Fig. 7. AM process selection model (Pikkarainen et al., 2021).

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.

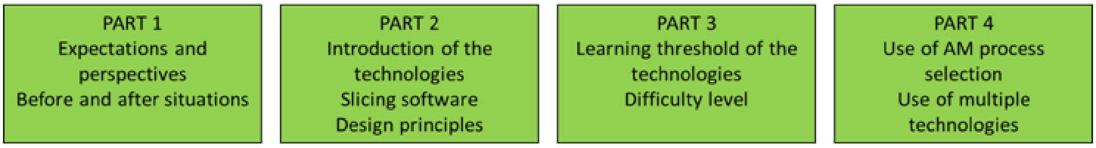

Fig. 8. Structure of the numerical questions.

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.

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.

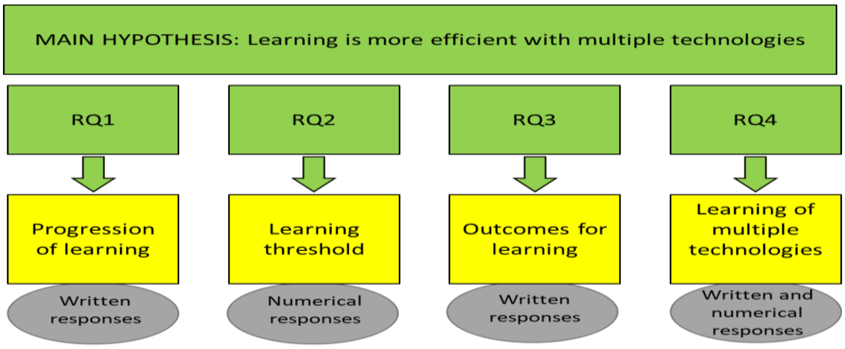

Fig. 9. Structure of the study.

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.

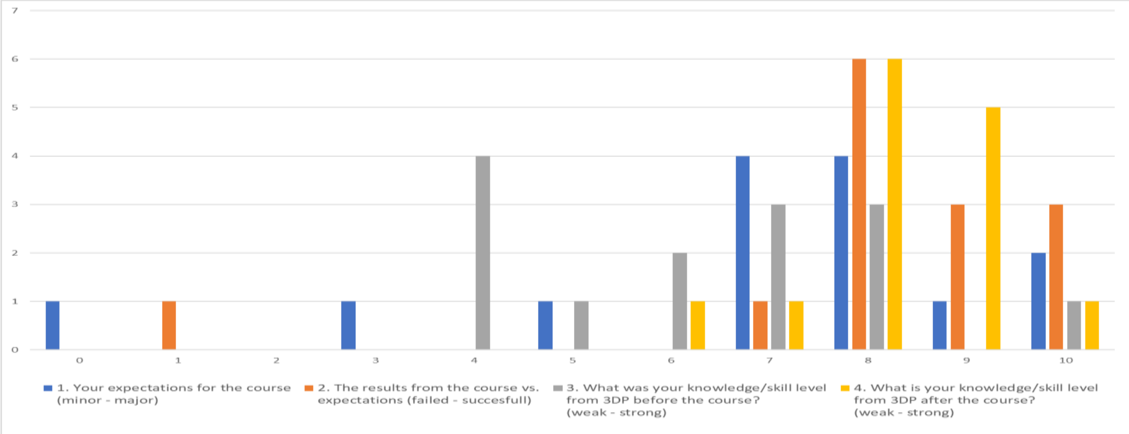

Fig. 10. Responses from part one of the numerical questions.

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.

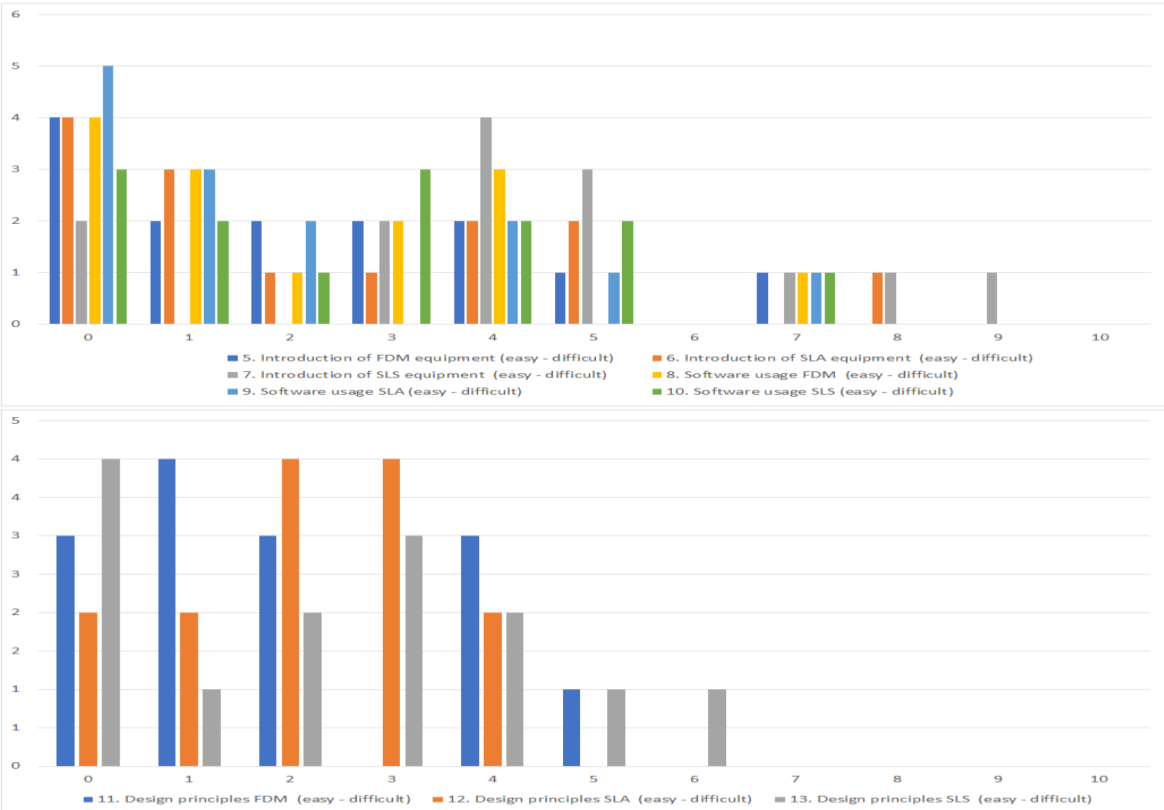

Fig. 11. Responses from part two of the numerical questions.

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.

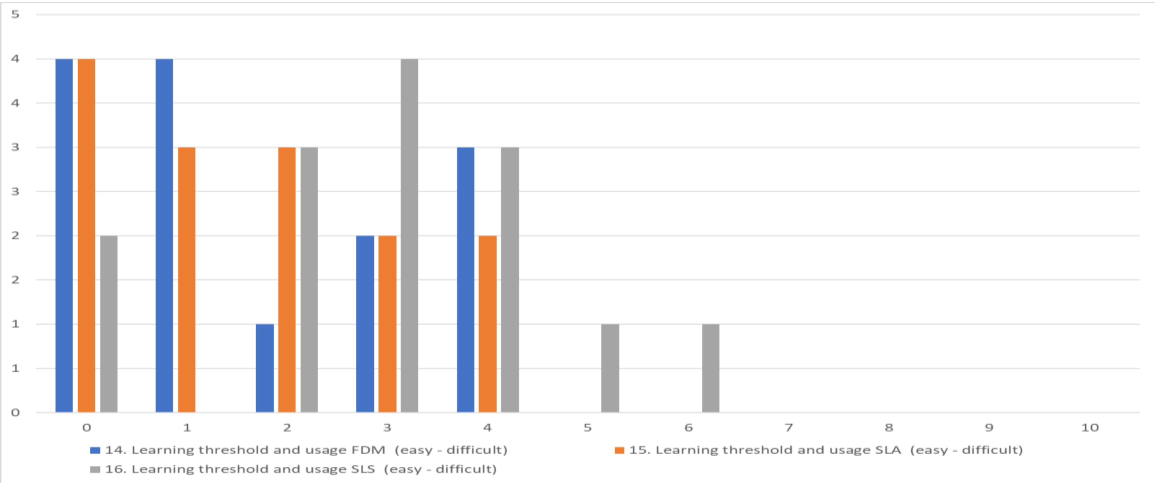

Fig. 12. Responses from part three of the numerical questions.

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.

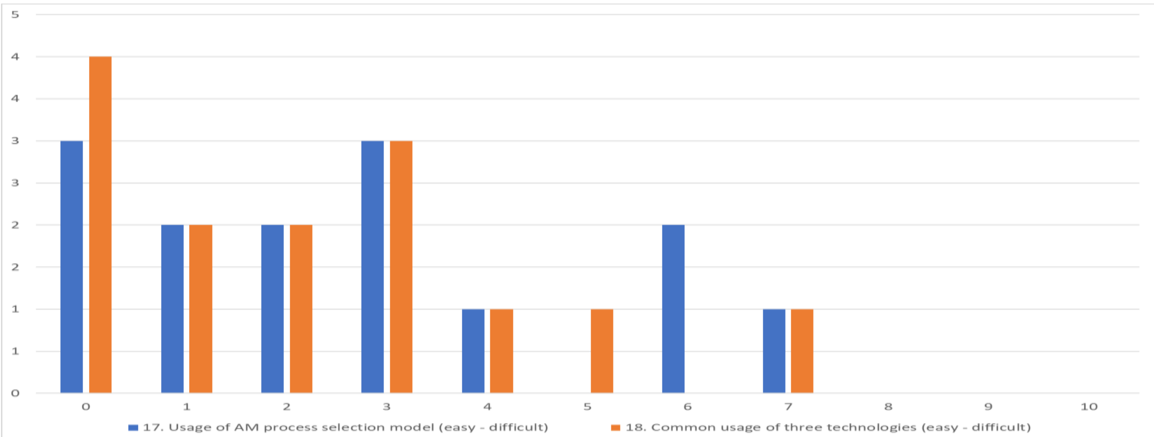

Fig. 13. Responses from part four of the numerical questions.

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 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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AUTHOR'S PROFILE

First Author
Ari Pikkarainen, M.Sc (Tech.) is working as a senior lecturer in the Mechanical engineering degree in Lapland University of Applied Sciences (Lapland UAS), Tietokatu 1, 94600, Kemi, Finland. Pikkarainen is a teacher of technical subjects such as AM, engineering design, mechanical calculations and energy technology. He has been working also as a mechanical designer in different areas such as steel and paper industry. His M.Sc. thesis was about creating a learning environment around AM for engineering student that combines traditional engineering design process into AM and it was done in Lappeenranta University of Technology (LUT). Pikkarainen has acted as a main responsible member of curricul--um development team in the Lapland UAS mechanical engineering degree in 2008-2012 and he acted as the main responsible teacher (guiding a team of teachers and R&D personnel) in renewing the Lapland UAS mechanical engineering curriculum in 2014-2017.

Second Author
Professor Heidi Piili, D.Sc. (Tech.), is working as professor at Research Group of Laser Materials Processing and Additive Manufacturing (LUT Laser & AM) of LUT University. Piili has more than 18 years' experience of laser processing (cutting, micro/mill processing, welding etc.) of various different materials. Her doctoral thesis in 2013 was about characterization and mathematical modeling of interaction between laser beam and material. Piili also graduated 2015 as professional teacher from Hame University of Applied Sciences. Piili has been working more than 12 years' with additive manufacturing, mostly concentrating to powder bed fusion of metallic materials. Nowadays, R&D agenda in ad--ditive manufacturing includes also plastic AM and also laser-based and arc-based directed energy deposition (DED). At the moment, Piili participates to national and international projects (academic and industrial) and also educates additive manufacturing and laser technology. She has more than 115 international publications in field of laser technology and additive manufacturing.

Third Author
Professor Antti Salminen, D.Sc. (Tech.) is working in Department of Mechanical and Materials engineering at University of Turku and a Docent in Manufacturing Technology at LUT University. He has more than 30 years of experience of laser-based manufacturing processes and welding in both academia and industry. He has been Principal Investigator in several research projects funded by national, Nordic and European funding agents. His specialization is in the process development, laser system development, product design for laser processing, monitoring of thermal processes especially for welding and additive manufacturing. He has published more than 100 peer reviewed scientific and more th--an 150 scientific conference publications. He is member of board of Finnish association for additive manufacturing and deputy member of board of Finnish Welding society and national delegate in IIW commissions I, IV and X. He has supervised 10 doctoral, 70 master, and 16 bachelor theses and is currently supervising 8 doctoral theses.