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

Ari Pikkarainen[1i],
Heidi Piili[2],
Antti Salminen[3]
[1]Department of Mechanical Engineering,
Lapland University of Applied Sciences,
Kemi, Finland
[2]Research Group of Laser Materials Processing
and Additive Manufacturing,
LUT School of Energy Systems,
LUT University,
Lappeenranta, Finland
[3]Mechanical Engineering,
University of Turku,
Turku, Finland

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

[i] Correspondence: email ari.pikkarainen@lapinamk.fi

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.

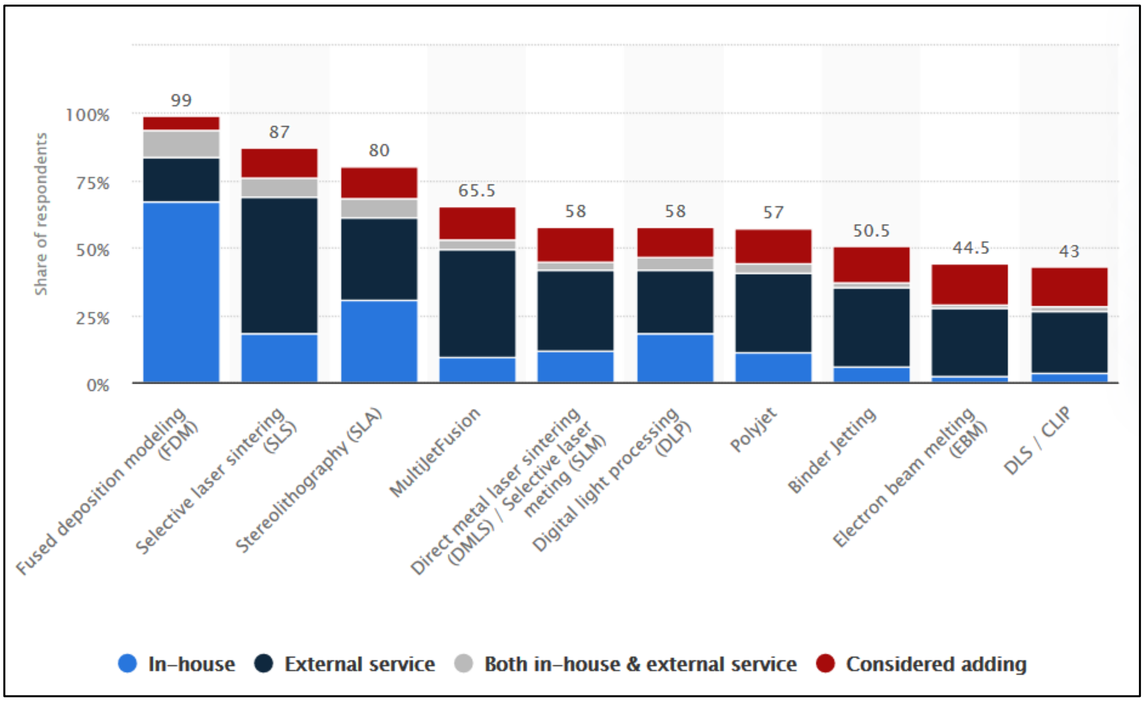


Figure 1: Most widely used 3D printing technologies worldwide in 2020 (Statista, 2020)

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).

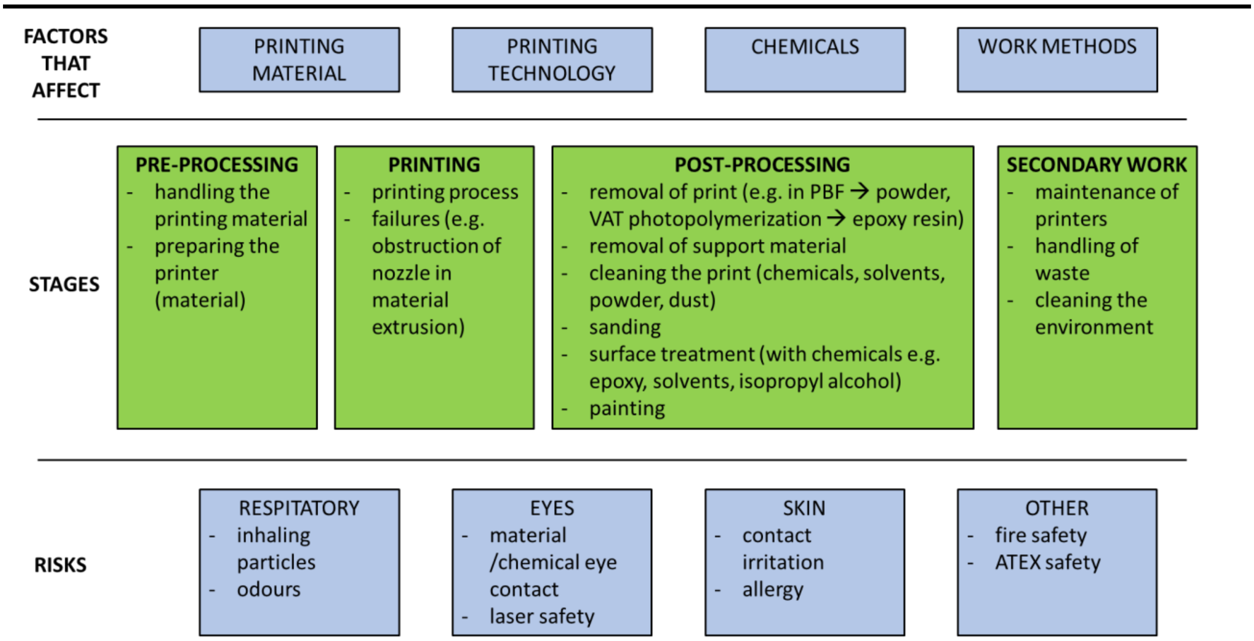


Figure 2: Different stages of 3D printing process including risks
(derived from Unwin et al., 2013, Stockmann-Juvala et al., 2016 and FIoOH, 2016)

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 $\left(5-10\,\frac{\mathrm{dm}^3}{\mathrm{s}}\right)/\mathrm{m}^2$. The guideline for office space air exchange rate was informed in the research to be $\left(1.5\,\frac{\mathrm{dm}^3}{\mathrm{s}}\right)/\mathrm{m}^2$. 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.

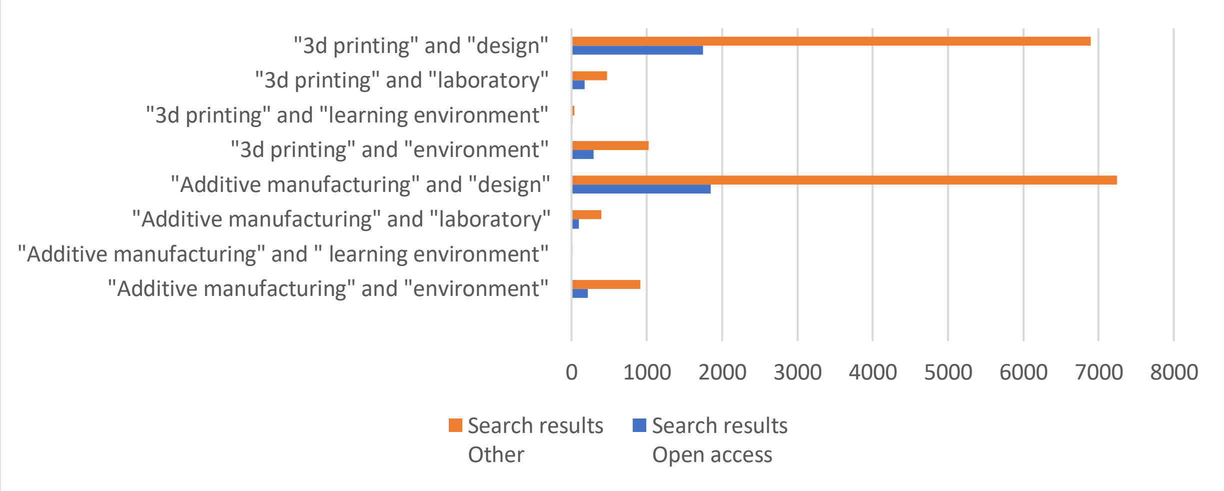
These authorised research results present a solid foundation to the design of a 3D printing environment presented in this study. The main conclusion from these to this study guiding the design of the laboratory state that every printer must be encased and equipped with air extraction to a separate air 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).

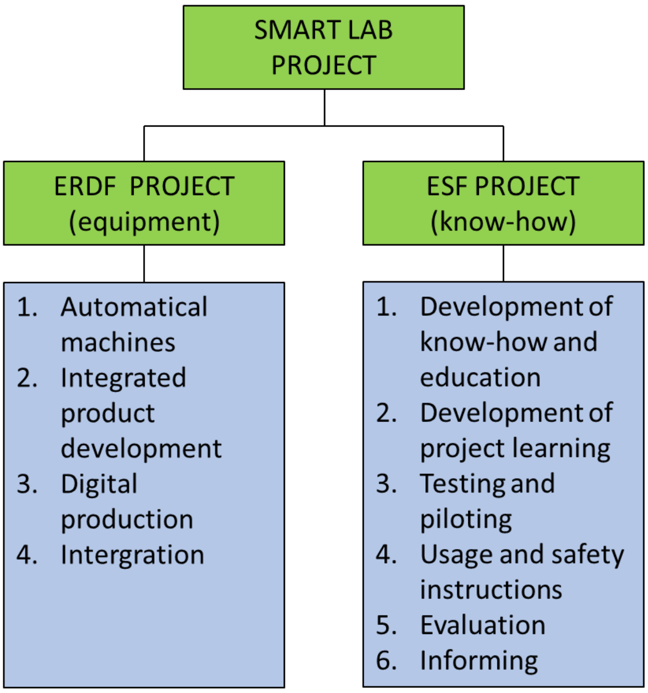


Figure 3: Description of the Smart Lab project (LUoAS, 2017 and LUoAS, 2018)

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.

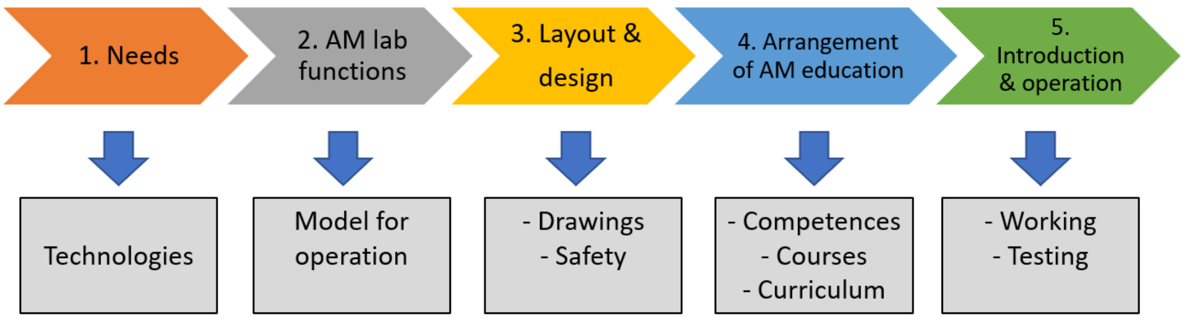


Figure 4: Process for creating Lapland UAS 3D printing laboratory

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.

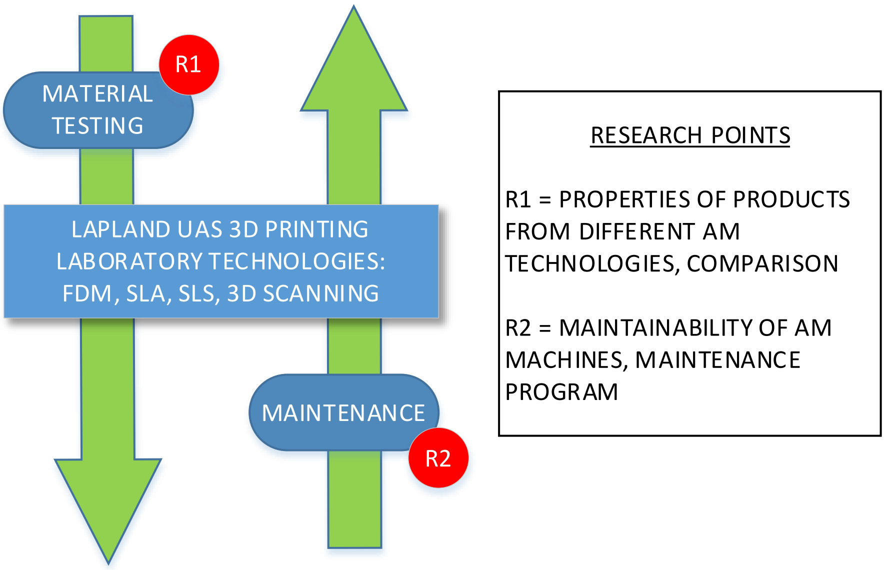


Figure 5: 3D printing laboratory section from the function model

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.

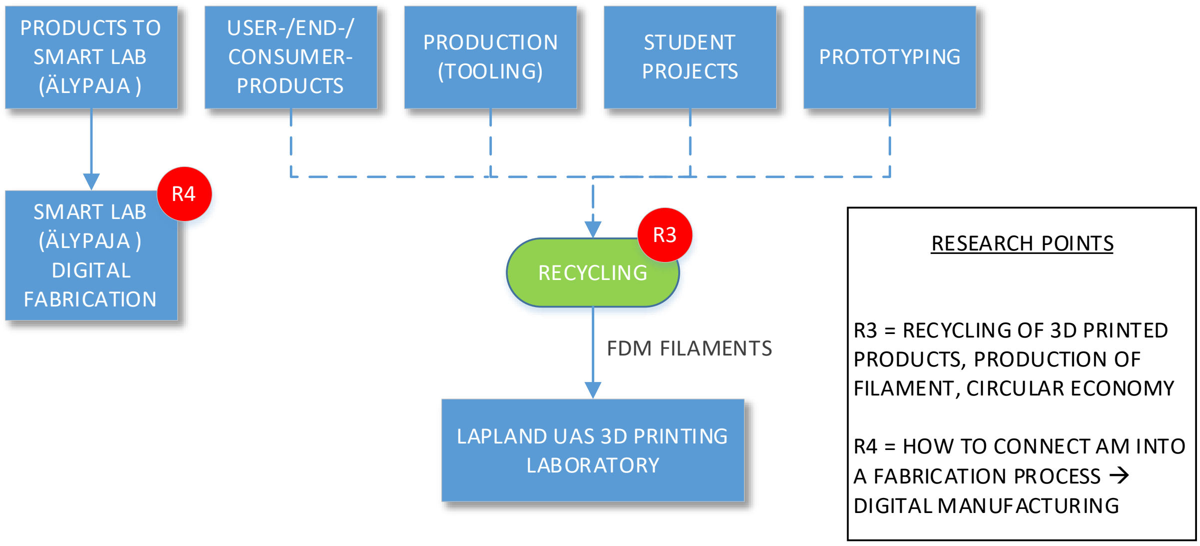


Figure 6: 3D printing laboratory outputs from the function model

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.

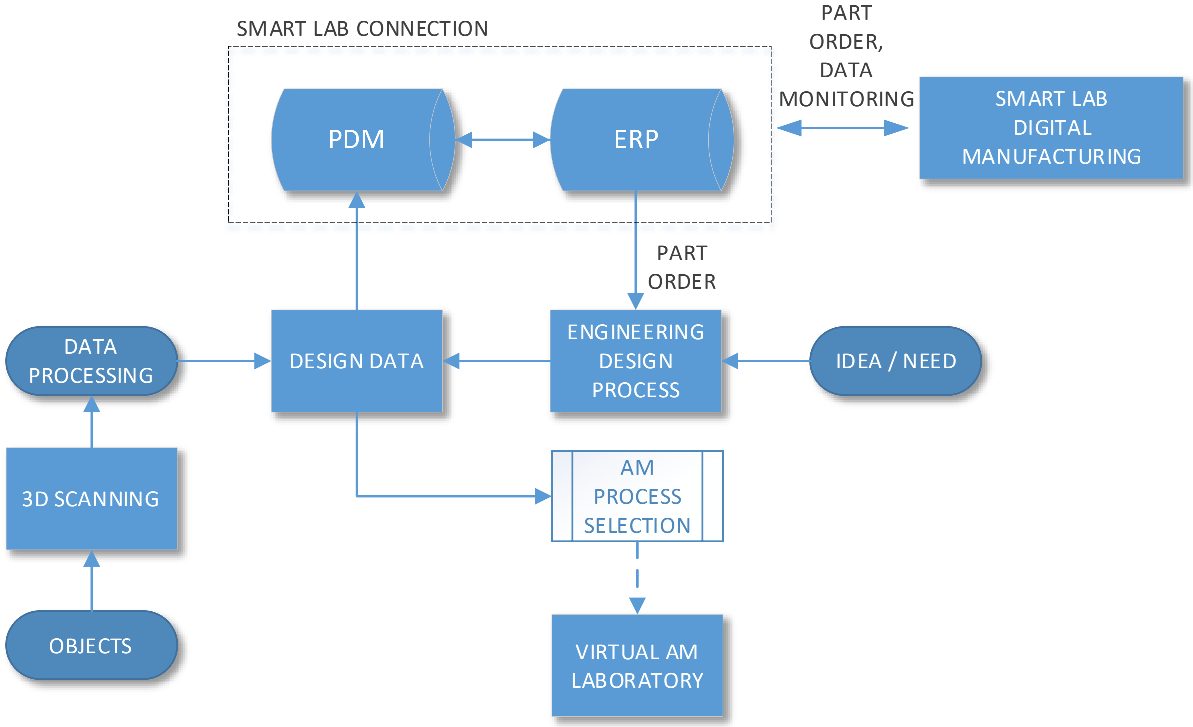


Figure 7. Engineering design aspect from the function model

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.

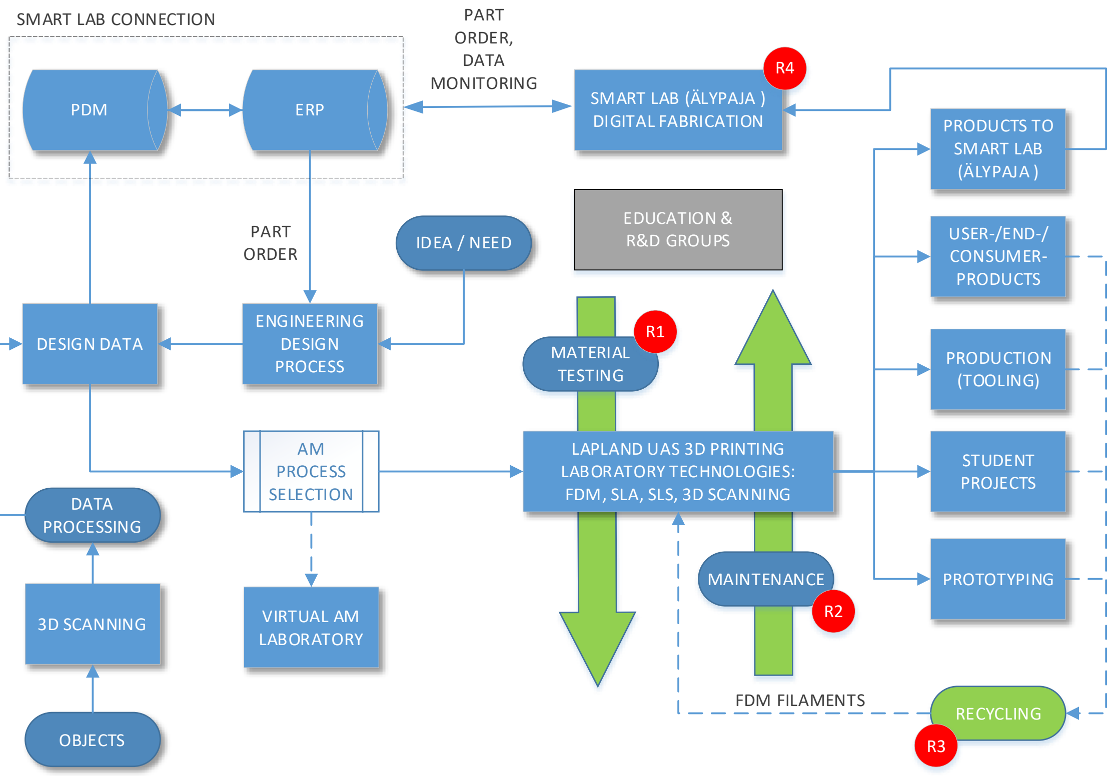


Figure 8: 3D printing laboratory function model

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.

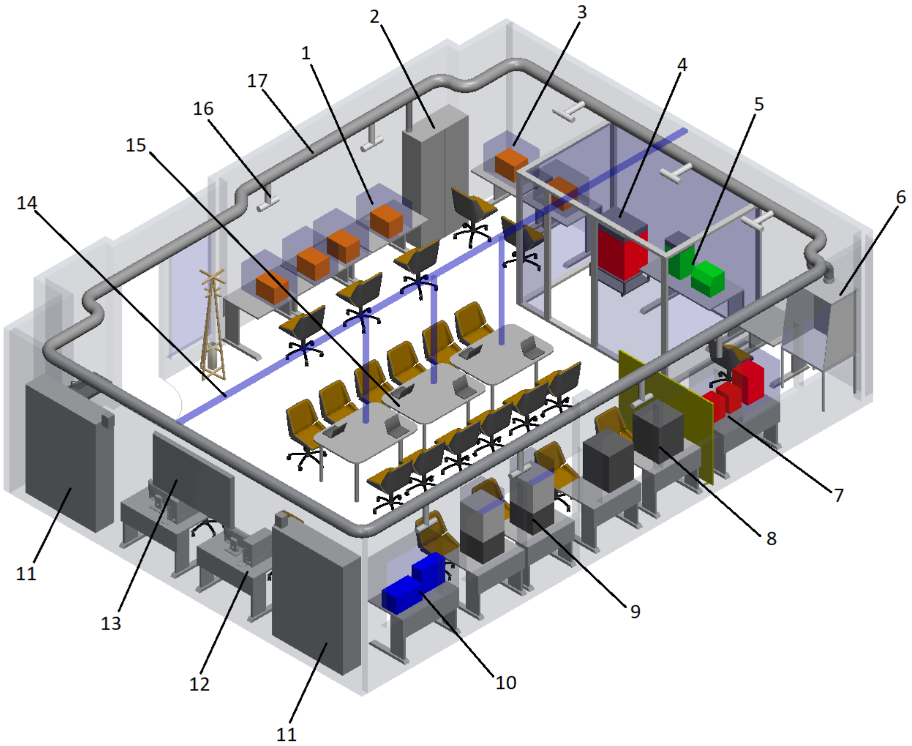


Figure 9: 3D printing laboratory layout

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.

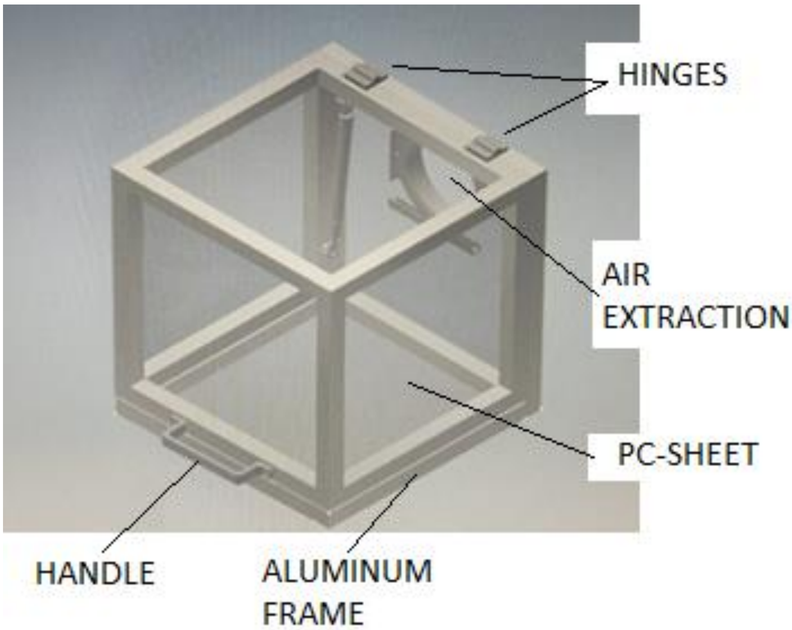


Figure 10: The design for closed aluminium/PC-casing for open FDM-printers (Lapland UAS student work)

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.

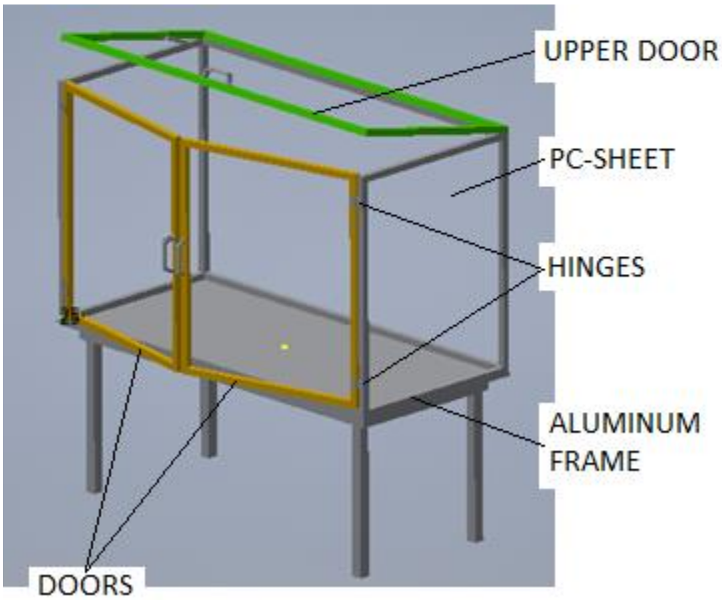


Figure 11: The design for closed aluminium/PC-casing for SLS/SLA printers (Lapland UAS student work)

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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About the Authors

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 3D printing, 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 3D printing for engineering student that combines traditional engineering design process into 3D printing and it was done in Lappeenranta University of Technology (LUT). Pikkarainen has acted as a main responsible member of curriculum 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. He is currently doing his D.Sc. (Tech.) studies at LUT and his doctoral thesis is about the connection between education and 3D printing. His dissertation is expected to be finished in summer 2021.

Professor Heidi Piili, D.Sc. (Tech.) is working as professor in field of laser processing and additive manufacturing. She is also team leader of Research Group of Laser Material Processing and Additive Manufacturing of LUT University (LUT). Piili was working within industrial additive manufacturing during year 2017 at Electro Optical Systems (EOS) Finland. 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 has been working more than 11 years with additive manufacturing, mostly concentrating to powder bed fusion of metallic materials. At the moment, she participates to national and international projects (academic and industrial) and also educates additive manufacturing and laser technology. She has more than 120 international publications in field of laser technology and additive manufacturing and her h-index is 11 (Google Scholar) and 8 (Scopus).

Professor Antti Salminen, D.Sc. (Tech.) is working in Mechanical Engineering at University of Turku and as 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 100 peer reviewed scientific and more than 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.

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