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3D PRINTING – CREATING LEARNING ENVIRONMENT FOR ENGINEERING STUDENTS

Examiners: Professor Antti Salminen
D.Sc. Heidi Piili

ABSTRACT

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3D printing – creating learning environment for engineering students

Master's thesis

2017

91 pages, 59 figures, 7 tables and 2 appendices

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Keywords: additive manufacturing, 3D printing, engineering design, DFAM, learning environment.

Purpose of this thesis was to design and create a functional learning environment to mechanical engineering students in Lapland University of Applied Sciences (LUAS). The learning environment combined traditional engineering design into additive manufacturing (AM) principles and practical 3D printing. Methods used in this thesis were divided into literature review and practical section.

Main outcome from the literature review were the fundamentals of AM and learning environment. It also included state-of-the art review of existing learning environments in Finland and rest of the world. Main outcome from the practical section were different models such as active learning model and process models such as 3D printing process chart model, AM design process model and learning assignment process models.

Active learning model recognizes the components of learning required to function in the environment. 3D printing process model presents the process for using the printers. AM design process model brings together product design model, engineering design and design for additive manufacturing (DFAM) principles including their stages. Learning assignment one model presents a process, which gives the student sufficient knowledge to perform practical 3D printing. Learning assignment two model presents a process, which aim to give the student practical information about DFAM and 3D printing in order for them to develop into independent users and experts of 3D printing technology.

Developing the environment in the future requires refining the existing learning assignments according to student feedback, the acquisition of new 3D printing technologies, efficient and functional facilities and different approaches in research. The environment can function also as a prototyping centre enabling student work training, prototyping services and information services to collaboration partners.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
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3D tulostus – oppimisympäristön luominen insinööriopiskelijoille

Diplomityö

2017

91 sivua, 59 kuvaa, 7 taulukkoa ja 2 liitettä

Tarkastaja: Prof. Antti Salminen
D.Sc. Heidi Piili

Hakusanat: lisäävä valmistus, 3D tulostus, koneensuunnittelu, DFAM, oppimisympäristö

Työn tarkoitus oli suunnitella ja luoda toimiva oppimisympäristö Lapin AMK:n koneteknii-kan opiskelijoille. Oppimisympäristö yhdistää perinteisen koneensuunnittelun, lisäävän valmistuksen periaatteet ja käytännön 3D tulostamisen. Työssä käytetyt metodit jaettiin kirjallisuuskatsaukseen ja käytännön osuuteen.

Kirjallisen osuuden tulokset olivat lisäävän valmistuksen ja oppimisympäristön periaatteet. Osuus sisälsi myös katsaukset olemassa oleviin oppimisympäristöihin Suomessa ja maailmalla. Käytännön osuuden tulokset olivat erilaiset mallit, kuten aktiivisen oppimisen malli sekä ja prosessimallit, kuten 3D tulostusprosessi, lisäävän valmistuksen suunnitteluprosessi ja oppimistehtäväprosessit.

Aktiivisen oppimisen malli tunnistaa oppimisen komponentit, joita tarvitaan ympäristössä toimimiseen. 3D tulostusprosessi esittelee mallin, jota tarvitaan tulostimien käyttöön. Lisäävän valmistuksen prosessimalli yhdistää tuotekehitysmallin, koneensuunnittelun ja DFAM periaatteet. Oppimistehtävän yksi malli esittelee prosessin, joka antaa oppilaalle riittävän tietotason 3D tulostukseen, kun oppimistehtävän kaksi malli esittelee prosessin, joka antaa oppilaalle käytännön tiedon DFAM periaatteista sekä 3D tulostuksesta, jotta hän voi kehittyä tekniikan itsenäiseksi käyttäjäksi ja osaajaksi.

Ympäristön kehittäminen tulevaisuudessa vaatii oppimistehtävien kehittämisen saadun oppilaspalautteen perusteella, uusien 3D tulostimien ja –tekniikoiden hankintaa, tehokkaat ja toimivat tilat sekä erilaisia lähestymistapoja tutkimuksen saralla. Ympäristö voi toimia myös prototyyppikeskuksena mahdollistaen oppilaiden käytännön työharjoittelun, prototyyppipalveluiden tarjoamisen sekä tietopalveluiden tarjoamisen yhteistyökumppaneille.

ACKNOLEDGEMENTS

I would like to thank my supervisors and instructors Antti Salminen and Heidi Piili for giving me the best guidance possible and giving me the possibility to see the wonderful world of AM. I would like to express my special thanks to Heidi Piili, who pushed me always into better result in writing this thesis and giving me the opportunity to write my first professional publications during this process.

I would like to thank also Merja Peltokoski and to the staff of LUT, who acted as the primus motor in my Mechanical engineering JEDI-studies guiding our group together with the other staff in LUT Technology. This fulfills my long-awaited dream to become MSc of technology.

My family and especially my beautiful wife deserves my deepest gratitude for giving me the opportunity to perform my studies during these two years. All the time spent with the studies was away from them and I hope I can compensate the lost time by any means possible.

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9.5.2017

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LIST OF SYMBOLS AND ABBREVIATIONS

ABS	Acrylonitrile butadiene styrene
AM	Additive manufacturing
CAD	Computer aided design
CCD	Charge coupled device camera
CDIO	Conceive – design – implement – operate
DFAM	Design for additive manufacturing
DFM	Design for manufacturing
FEA	Finite element simulation
FDM	Fused deposition modeling
FHTW	Fachhochschule Technikum Wien
LCA	Life-cycle assessment
LUAS	Lapland University of Applied Sciences
NURB	Nonuniform rational B-spline
PLA	Polylactic acid
RPS	Rapid prototyping service
SASKY	Sastamala municipal education and training consortium
STL	Stereo litography cad format or standard triangulation language
TAMK	Tampere University of applied sciences
TTY	Tampere University of technology

1 INTRODUCTION

Traditional mechanical engineering science has always been seen as a part of heavy industry and the reputation of a stiff, non-renewable trade still remains within people. The reality nowadays could not be more far away. New modern technologies are daily part of the regular engineering work and just to keep up with the development, the engineering trade has to renew itself all the time and present several different skills in order to succeed. This sets high demands to engineering education in universities, universities of applied sciences and other technical schools. The pressure from the industry forces education to find new ways to teach engineering to the students. (Crawley et al. 2014, p. 1-2.)

Additive manufacturing (AM) is one possibility for refreshing engineering education. The technology itself does not revolutionize the whole trade but if offers good way to guide the engineering thinking to a different direction in which new possibilities from design to manufacturing are realized. The creativity in thinking is important to harness in engineering design process and also in engineering in general. When thinking about traditional product development process from idea to finished product, versatile thinking is a key factor in creating a successful product. (Gibson, Rosen & Stucker 2015, p. 9.)

This is the reason why creative thinking process needs new ways to renew itself and AM is potential candidate for this. Many academic institutions even in elementary school level have taken AM as a part of the academic environment and are developing the usage of the equipment for educational purposes and training the technology to students. (Bates 2015.)

AM can be seen more than an extent of the manufacturing process and in this thesis it is handled as a tool for strengthen engineering education.

1.1 Background

The background of the thesis comes from the acquisition on 3D printing equipment to Lapland University of Applied Sciences (LUAS) unit of technology, which situates in Kemi, Finland. LUAS situates in three different city in north Finland: Kemi, Rovaniemi and Tornio. LUAS has four main focus fields as follows:

- social services (in Rovaniemi and in Kemi), health (in Rovaniemi and in Kemi) and sports (in Rovaniemi)
- business and culture (in Tornio)
- travel and tourism (in Rovaniemi)
- industry and natural resources (in Rovaniemi and in Kemi).

LUAS has about 5000 students in different degrees and around 500 employees. The unit of technology situates in Kemi and holds degrees in mechanical and electrical engineering. 3D printing is relatively new technology in LUAS to be used in learning; some small 3D printers have been tested during 3D computer-aided design (CAD) courses courses in the past just to get to know the technology with the students. Now the scale of the current acquisition enables efficient introduction of the technology and solid integration to the mechanical engineering degree.

The 3D printing equipment is a part of the modernization of mechanical engineering education. Reason for the modernization is to respond to the requirements from the industry and work life and also to look engineering education from new point of view. The modernization consists of renewing the whole curriculum, designing the courses in a completely new way and also using different learning environments more efficiently. The new curriculum will be taken into use in fall semester 2017 with the incoming new students. The renewing of the curriculum happens in every degree program of LUAS during 2016-2017. Activities in 3D printing will be integrated to the CAD design laboratory to create completely new learning environment in which the student can learn the possibilities of additive manufacturing in engineering design area and see the process from 3D model to a finished product.

1.2 Research and the methods

The main research problem of the thesis is creating a functional additive manufacturing learning environment for mechanical engineering students in LUAS. Learning environments in the university are connected to different functions of the degree such as machine automation, CAD designing or energy technology. The basic principle is to function in a real-life environment safely, usually in a laboratory solving a problem as a project-based learning. Figure 1 presents the basic idea of a learning environment in LUAS Technology.

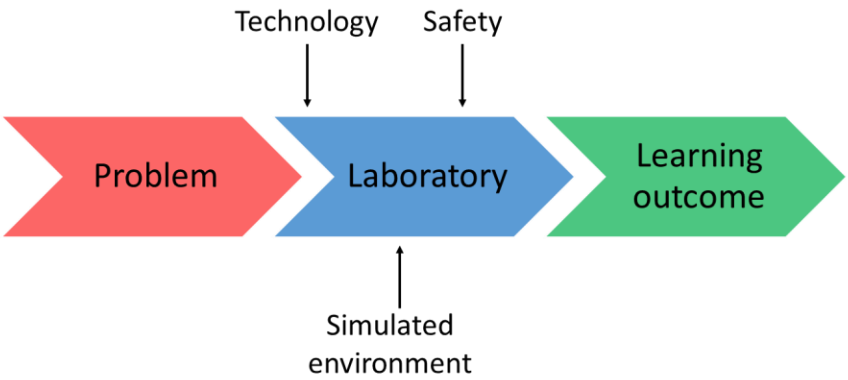

Figure 1. Principle of a learning environment.

The main research question is derived from the problem and can be described as follows:

"What is the effective way to learn mechanical design work via additive manufacturing technology?"

Part research questions are built from the main research question, which guide the thesis process:

1. What are the fundamentals of additive manufacturing teaching and learning?
2. What are the fundamentals of AM technology, which should be learned by the students?
3. How to exploit additive manufacturing in engineering design process?
4. What are the efficient learning assignments from AM for mechanical engineering students?
5. What are the desired learning results and how they are evaluated?

The thesis is divided into two sections and the research methods are built from these. The theoretical section consists mainly on literature review with cross-referencing information and it gives the foundation to the experimental part. In addition, the documentation of tacit knowledge gives important content to the theory section. This includes the methods used in AM and engineering design teaching. The experimental part consists of data triangulation in which the theory is applied in the 3D modeling and comparing the results of the 3D printing tests. 3D models are made for the printing tests and theory is applied in the modeling process.

Especially the information given by the literature is compared to the test results and therefore the connection between design and manufacturing will be explored.

1.3 Objectives and limitations

The main objective of the study is creating a functional additive manufacturing learning environment to LUAS Unit of Technology in Kemi. Important part of this is to acquire basic knowledge from AM to teaching and learning purposes, main part of this is to introduce the technology and make necessary tests for sorting out the functional qualities of the equipment and especially the possibilities and limitations of the technology. The technology used here is 3D plastic printing and 3D scanning. Second main objective is to create AM learning assignments from different topics to the students.

The limitations of the thesis are divided into three sections. First, the main theories applied are limited to product design process including prototype creation, engineering design process in pre-design phase and to additive manufacturing theory. Second, the technological theory section is limited into plastic printing theory called fused deposition modeling (FDM) and to table-sized 3D scanning equipment and its utilization. Third, the empiric section is limited into the introduction of the equipment, making initial tests for the equipment and testing the learning assignments and iterating the instructions for the assignments. In this section, students are making the tests from the point of view of main user. Figure 2 presents the limitations and the outcomes they produce the main result included.

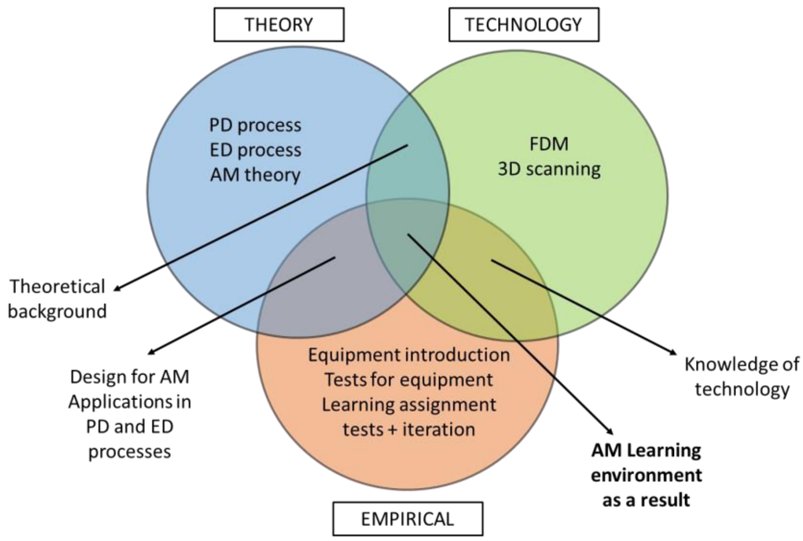

Figure 2. Limitations and outcomes of the thesis.

1.4 LUAS mechanical engineering education introduction

The mechanical engineering degree is a part of the school of industry and natural resources in LUAS. Main areas of degree in education are:

- engineering design and product development
- production technology
- machine automation (pneumatics and hydraulics)
- material science
- maintenance
- energy technology.

The degree has strong history especially in mechanical designing which includes CAD designing, strength and statics calculations and material knowledge amongst other engineering areas. Students can specialize in mechanical, production or mining technology. The education includes also an engineering design office, which collaborates with different partners in cooperation by making design work by order. In this environment, the students can work in real life situation and apply all the things they have learnt as seen in figure 3.

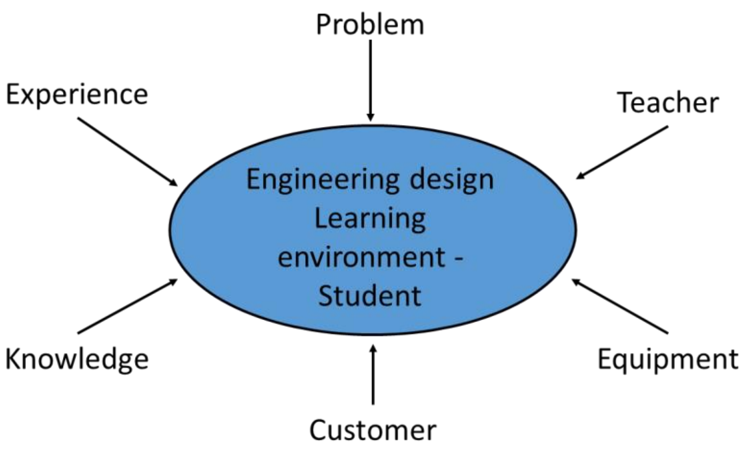

Figure 3. Principle of engineering design learning environment.

Most of the actual work happens in CAD design laboratory which has computers with two displays with all the necessary software installed (AutoCAD, Inventor, Microstation etc.). The laboratory also has a full size paper printer (A0 size) and –cutter for reviewing technical drawings in full size.

2 ADDITIVE MANUFACTURING – 3D PRINTING

AM (known also as 3D printing) is a technology in which part is designed via 3D CAD program as a model. After this, it is fabricated with certain technology instantly without any need for conventional process planning or acquiring tools for fabrication. This allows the user to create real-life parts from CAD model and therefore realize the design as a touchable and testable object. The fabrication process with AM consists of creating the part from layers that are read from the 3D CAD model as seen in figure 4. This deposition of individual layers is the foundation of AM. (Gibson et al. 2015, p. 2.)

Figure 4. Teacup model with individual layers presented (Gibson et al. 2015 p. 3).

AM technology as a term is commonly referred to a process in which materials are joined together to create real objects from 3D CAD model layer by layer whereas 3D printing refers to fabrication process by deposition of material usually by certain printing head or nozzle (ASTM F2792-12a 2013, p. 1-2). Even though the standard definition distinguishes these two terms apart from each other, common opinion is that the term 3D printing will be the common term to be used when describing AM technologies and this has been proven even by the media (Gibson et al. 2015, p. 8).

The process of AM consists of creating the desired 3D model by a 3D CAD program and converting the model into a STL (stereo litography cad format or standard triangulation language)-format. The STL-file consists of triangles, which control the quality of the model.

The quality of the file improves when the size of the triangles is reduced. (Wong & Hernandez 2012, p. 3.) The effect of the triangle quality can be seen in figure 5.

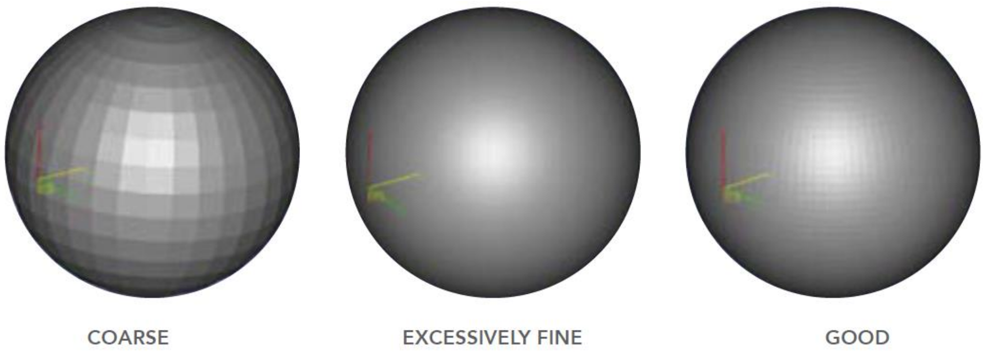

Figure 5. Quality of the STL-file. (Stratasys direct manufacturing 2014, p. 4).

This file is then transferred into the AM machine via separate program in which all the attributes of the printing process can be edited and controlled. The fabrication stage via AM consists of different phases according to the used method. (Gibson et al. 2015, p. 4-6.) The principle of generic AM process in presented in figure 6.

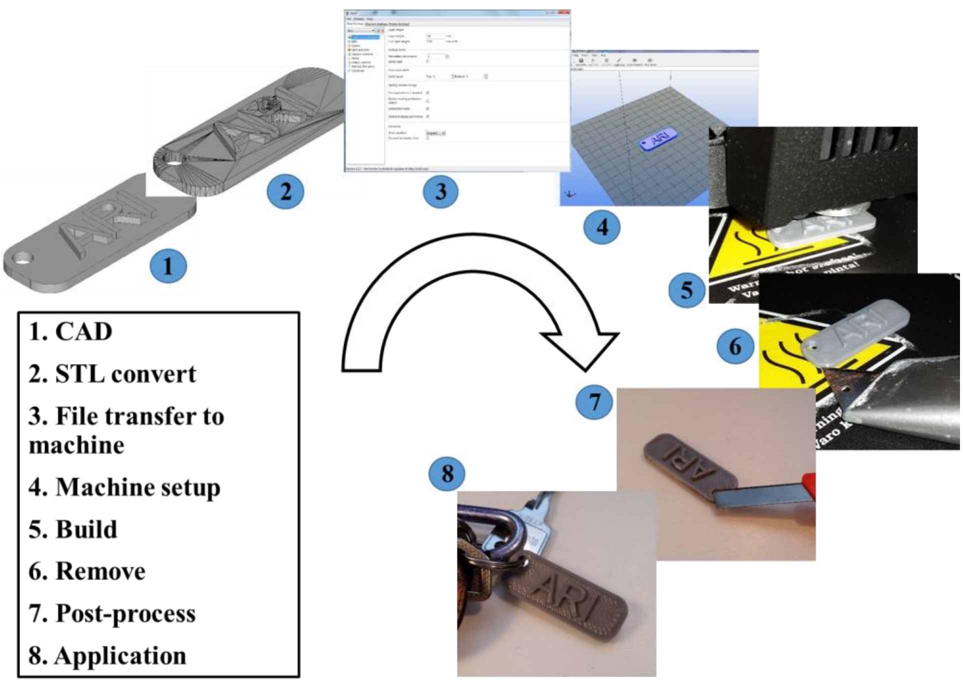

Figure 6. The generic AM process chain (Gibson et al. 2015, p. 5).

The AM technologies are divided into 7 categories according to Conner et al. (2014, p. 64), as follows:

1. powder bed fusion
2. material extrusion
3. material jetting
4. vat photo-polymerization
5. binder jetting
6. sheet lamination
7. direct energy deposition.

In this thesis, only material extrusion with plastic is presented because this topic in essential for understanding experimental part of this work. Other technologies would also fit to the idea of the learning environment and they can be used later.

2.1 Basics of FDM

3D printing with material extrusion is at the moment most popular technology when comparing market numbers (Aniwaa 2016). Figure 7 presents the market shares.

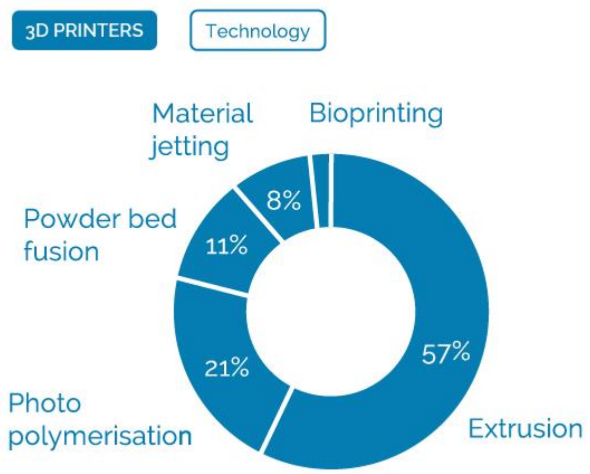

Figure 7. Shares of 3D printing technologies in the world (Aniwaa 2016).

Material extrusion is based on molten material, which is extruded through a printing head. The most popular and used material extrusion technology is fused deposition modeling which was developed in the U.S. by a company called Stratasys. (Gibson et al. 2015, p. 147, 160.) FDM has a quite short work cycle, the technology is easy to learn and use, high accuracy for dimensions and integration to CAD programs is relatively simple. These are also the reasons why FDM is popular AM technology at the moment. (Boparai, Singh & Singh 2014, p. 282.)

FDM technology consists of equipment, which feeds a plastic filament wire into a liquefier chamber. The chamber is heated into a temperature suitable for melting desired plastic material according to its melting point. The filament softens and melts inside the liquefier and the filament pulling rolls pushes the molten plastic through the nozzle along with the non-molten filament. The energy required in the melting process is produced by a heater connected along with a thermistor to the nozzle. (Carneiro, Silva & Gomes 2015, p. 769-771.) Figure 8 presents the structure of the printing head. The temperature should be as low as possible in the melting point area to avoid material degradation inside the chamber or even burning which could leave burn residues inside the chamber (Gibson et al. 2015, p. 149).

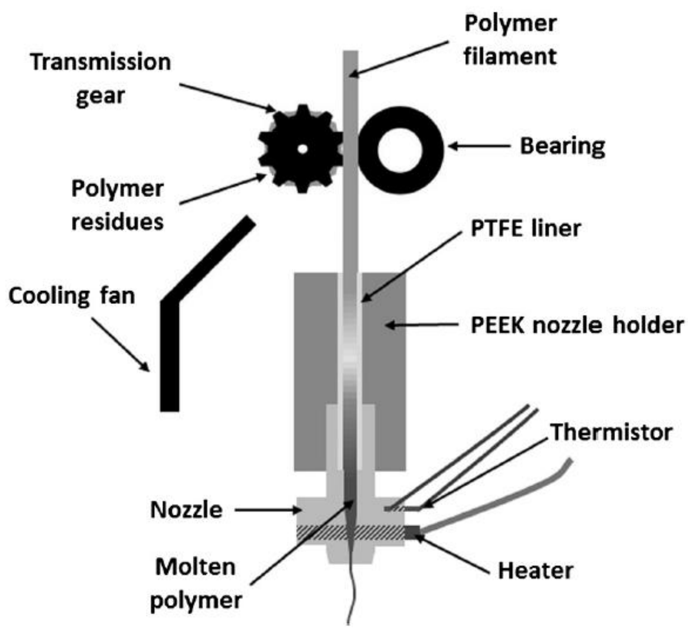

Figure 8. Structure of the printing head (Carneiro et al. 2016, p. 771).

The molten filament is deposited onto the platform or already extruded surface by layers where it cools into room temperature and bonding with the base material (Jun et al. 2016, p. 332) as seen in figure 9. The height of the extruded layer depends on the G-code generated by the slicing software while the width of the layer depends on the diameter of the extrusion nozzle.

The wall thickness is related to the thickness of the layer. The common rule is to multiply the thickness of the layer by two and using it as the minimum wall thickness. If a more robust structure is desired, the layer thickness should be multiplied by four. (Stratasys direct manufacturing 2014, p. 5-6.)

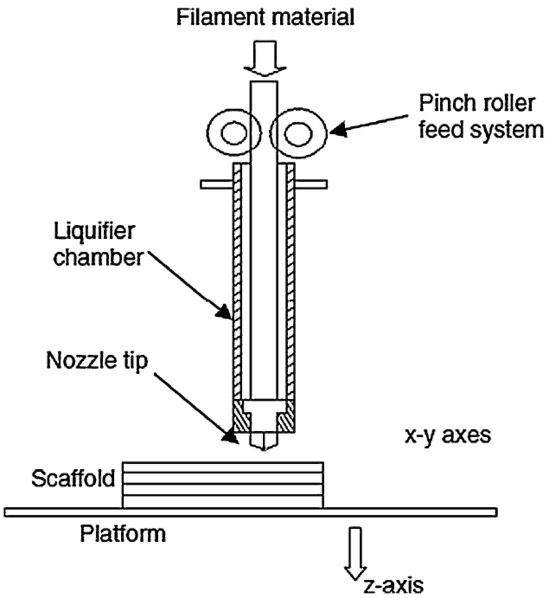

Figure 9. Basic principle of extrusion based printing system (Gibson et al. 2015, p. 150).

This forms the work cycle of the process as the platform moves down for the deposition of a new layer. As this happens, the layers are bonded together by diffusion produced by the thermal energy from the liquefied plastic filament. The same diffusion mechanism happens also with the adjacent layers as with the overlapping layers during printing. (Kousiatza & Karalekas 2015, p. 400.) The positioning of the deposited lines is produced by the equipment. Voids between the lines and layer weakens the mechanical properties of the printed object. If the cooling is too quick in the bond, it will lead into inner stresses in the object, which causes weakness in the bond between the layers. This can lead to deformities like cracks, delamination of the layers or even the whole fabrication process might fail. (Wang et al. 2016, p. 152.) The effect of voids and maximizing object strength by avoiding them is presented in figure 10 (Gibson et al. 2015, p. 159).

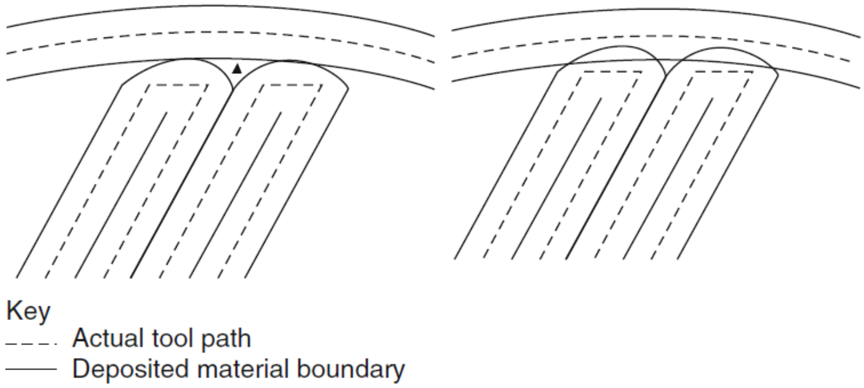

Figure 10. Basic principle of extrusion based printing system (Gibson et al. 2015, p. 159).

2.2 Support and basic instructions for design

Support structures are meant to produce support for overhanging structures. Overhang is a part of the geometry printed from certain surface and it has no material below the geometry, it is defined as a parallel to the printing platform. If this kind of geometry is not supported, the filament fails to print. (Micallef 2015, p. 98.) General rule for self-supporting surfaces is around 45 degrees depending on the material and printing variables (Stratasys direct manufacturing 2014, p. 7). An example of support structure can be seen in figure 11.

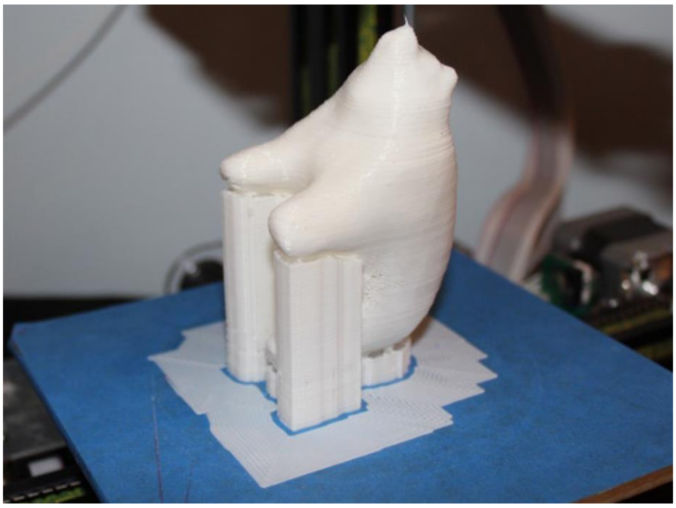

Figure 11. 3D printed bear with support structure (Horvath 2014, p. 106).

Threads with sharp edges should be avoided since it is impossible to create absolutely sharp corner with FDM round nozzle, radius is always dependent from the diameter (Gibson et al. 2015, p. 164). If thread needs to be included, it should contain rounded edges or use external thread insert in the part (Stratasys direct manufacturing 2014, p. 7).

When printing assembly parts that will be connected, right gap between the parts should be included to avoid them to be melted together in the extrusion process. Basic minimum clearance in Z-direction is usually same as the used layer thickness. In X- and Y-direction, the minimum gap should be at least the same than the width of extruded layer. (Stratasys direct manufacturing 2014, p. 7.)

2.3 Technology and equipment

The main parts of FDM equipment consists of the filament spools, extrusion head and build platform (Additively 2015). Basic structure of FDM equipment is presented in figure 12.

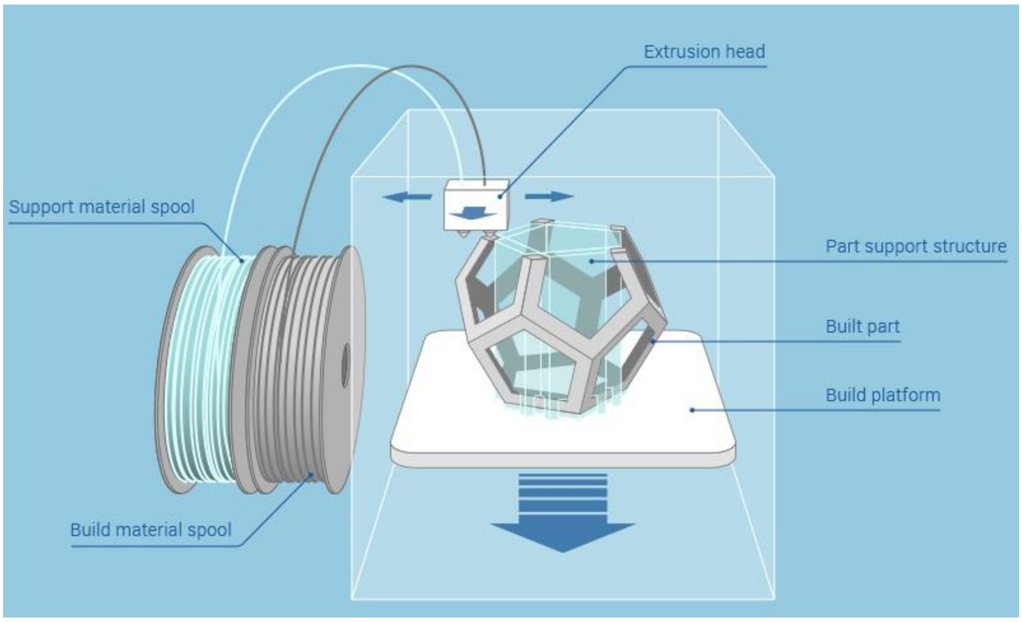

Figure 12. Basic principle of FDM equipment (Additively 2015).

The extrusion process starts from unwinding the plastic filament material from a roll. The feeding of the wire is handled with pinch roller system, which is located in the extrusion head. Movement of the extrusion head depends of the printer type. (Kun 2016, p. 208.) The mechanism for dual extrusion head feeding the wires can be seen in figure 13.

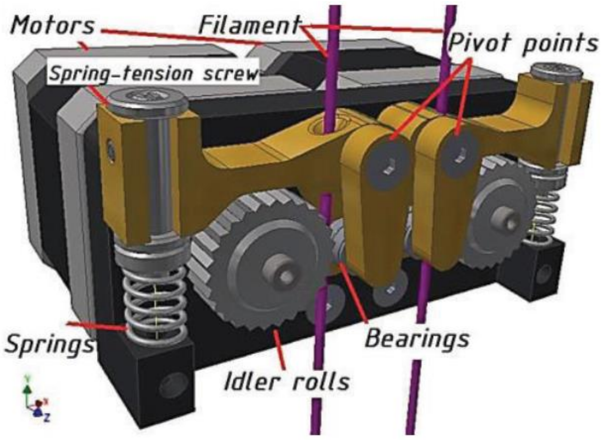

Figure 13. Filament feeding equipment (Kun 2016, p. 208).

The filament feeding equipment feeds the filament to the printing head, which contain the liquefier for melting the plastic. The head includes also a cooler, which regulates the temperature of the printing head. (Kun 2016, p. 209.) Example of the printing head can be seen in figure 14.

Figure 14. Example of an extrusion head (Kun 2016, p. 209).

The extrusion head contains an input for the filament and sinks for dissipating excess heat. The heating unit melts the plastic and the extrusion is done through the nozzle. (Kun 2016, p. 209.) Example of the extrusion unit with heater can be seen in figure 15.

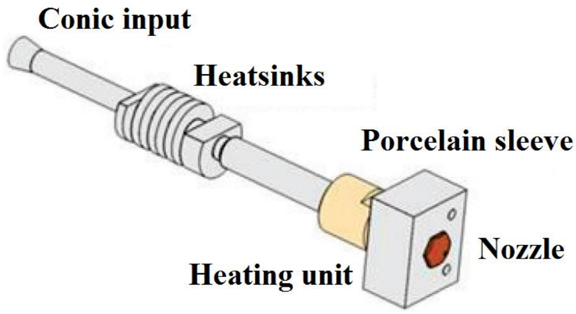

Figure 15. Example of a nozzle head assembly (Kun 2016, p. 209).

As the material solidifies after extrusion, the shrinkage caused by cooling can be minimized by using a chamber, which is heated. The platform where the material is extruded is a XY-plane table and is usually moved by roller screw system. (Gibson et al. 2015, p. 149-154.)

The popularity of the technology can be seen nowadays as a variety of different printers. Printers are built in very compact shape and easy to use even for a household use and the prices are starting to be in a reasonable level. (Makerbot 2016 & Stratasys 2016b.) Examples can be seen in figure 16.

Figure 16. Examples of commercial FDM printers (Makerbot 2016 & Stratasys 2016b).

2.4 Materials

The printable material in FDM is commonly made of plastic such as PLA (polylactic acid) or ABS (acrylonitrile butadiene styrene). Other materials used are nylon and different elastomers. The filament material is supplied in spools and the typical diameters are 1.75 mm and 3 mm. Different filament material behave in different ways and the material should be selected according to the application. (Horvath 2014, p. 83.) The most common printable materials with typical characteristics are presented in table 1.

Table 1. Characteristics of typical filament materials (Horvath 2014, p. 83).

Material	Print temperature (deg. C)	Bed temperature (deg. C)	Speed
PLA	210	60	Normal
		Unheated/blue tape	Normal
ABS	240	115	Normal
Nylon 618	240	Unheated/Garolite	Normal
HIPS	240	115	Normal
Elastomer	210–225	Unheated/blue tape, bare glass	Very slow
PET	Nominally 212–224; some users suggest 250	80	Slow
Polycarbonate	> 270	Very high	Varies

2.5 Workflow and software

The process from 3D model to an actual printed object is called workflow. It consists of the phases and actions that need to be done in order to print an object. (Evans 2012, p. 27-28.) The principle of the workflow can be seen in figure 17.

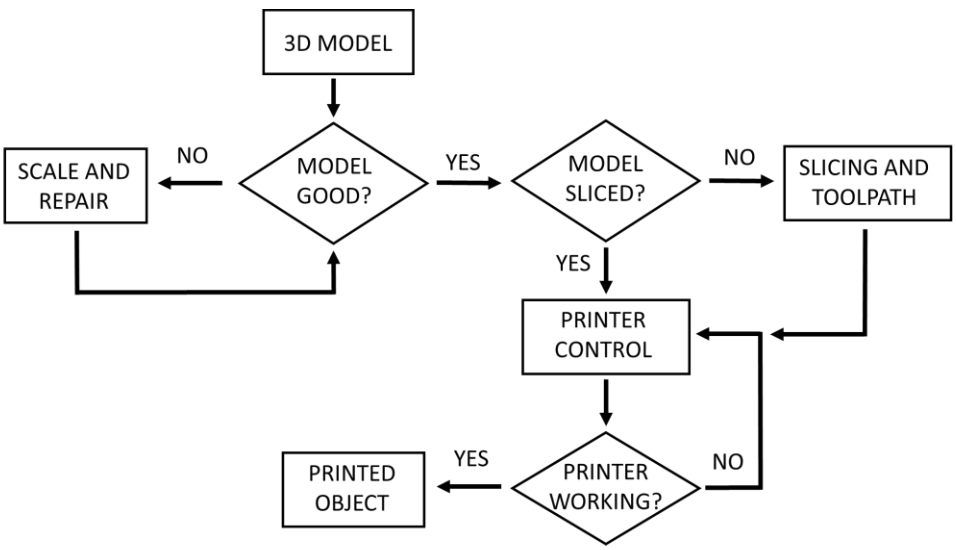

Figure 17. Workflow of a 3D printer (Evans 2012, p. 28).

The 3D model produced with CAD-program will be imported to the workflow as a STL. Main operation of the workflow will be done with separate software which includes functions for slicing the model, handling algorithms for retopology, generation of support structures, orientate the printable object and more commonly, validate the 3D CAD model for printing output. There are several alternatives for the software, some of them are freeware, some come with the purchased printer and some are even more sophisticated and commercial softwares. (Micallef 2015, p. 21.)

2.6 Safety and health issues

3D printing as a manufacturing method varies from conventional methods like machining by its safety level. Modern printers are built compact so that the actual printing happens inside the encased printer, which minimizes the possibility for hazard. Main physical hazards while removing the printed object or reacting to an error situation are burning of fingers and hands to hot surfaces of printing platform of print nozzle. The largest safety issue concerns respiratory hazard. As the printable material such as plastic melts during the process, fine nanoparticles are released. For example using PLA as printing material size of the particles can be smaller than 1/10 000 of a millimeter. The flow of the nanoparticles can be even 20 billion particles during each minutes to surrounding air. While using ABS the flowrate can be even as high as 200 billion particles per minute. These present a health hazard since nanoparticles interact with different parts of the human body such as skin and lungs not to mention nervous system and brain. If the exposure amount of particles is too big, it can lead to harmful effect to health such as asthma symptoms or strokes. This has to be taken into account when performing the printing. If the printer do not have encased structure with air-filtration system, placement of the printer should be planned closely. (Carnegie Mellon University 2016.)

3 3D SCANNING

Reverse engineering as a part of the additive manufacturing process uses a scientific study of measurement called metrology to read objects and forms into 3D CAD data. This data can then be used as an information in creating 3D models to be handled with computer software. This is called scanning the existing objects for AM purposes. Other possibility is to scan already 3D printed objects and inspect the accuracy of the part while comparing it to the 3D CAD model data. (Macy 2015, p. 2486.) This is the first step in reverse engineering, as the object is rebuild by using technology such as scanners or different probing methods (Wang 2010, p. 25).

3.1 Basics

Laser scanning as a process is basically reconstructing the existing object into data. According to Wang (2010, p. 25) the process of this reconstruction can be divided into four separate stages:

1. Acquiring data.
2. Polygonization of the data.
3. Refinement of the data.
4. Generating the model.

The data acquisition is largely responsible for the quality of the result and it can be done by using three-dimensional scanner or probe, which takes contact with the object. The information provided by the equipment is feeded into a software, which completes the polygonization. Usually the software comes with the equipment. In the polygonization process, a mesh made of polygons is created which consists of edged, faces and vertices. (Macy 2015, p. 2495.) The next step of the process refines the collected data by separating and grouping the data, which are done by segmentation. After this different mathematical methods are used to fit the surfaces and making constraints for several surfaces. (Wang 2010, p. 25-26.) The scanning process is presented in figure 18.

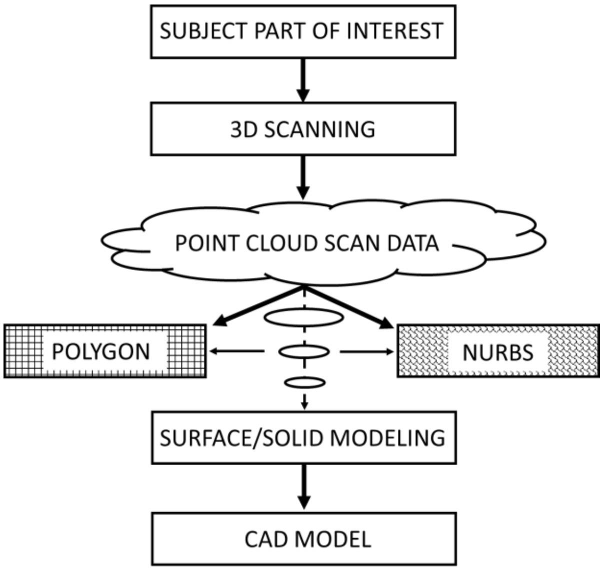

Figure 18. 3D scanning (Wang 2010, p. 26).

The equipment scans the object and creates a point cloud data, which consists of set of points. The amount of measured points can rise up to millions. (Macy 2015, p. 2488.) This set of information cannot be used directly by a CAD program so it must be converted into another format such as mesh made of polygons or to NURB (nonuniform rational B-spline model). These are then proper sets to be imported into CAD program as a surface or solid model. (Wang 2010, p. 26.)

3.2 Technology and equipment

The laser scanning technology investigated in the thesis is based on non-contacting methods. In the technology, two-dimensional cross section images and point clouds are seized by sending light from the scanner to the object. The light reflects from the surface of the object and is received back. The most common way to observe the received light is triangulation in which the coordinates and point of the surface are specified. The equipment consists of a projector, which emits the light and a camera, which receives the light. The camera is photosensitive and is usually called a CCD (charge coupled device camera). (Raja & Fernandes 2008, p. 37-38.) The camera is a certain distance away from the projector, the software of the equipment triangulates the information by using different algorithms. This information in calculated as 3D data, which can be used to create a 3D model. The process is also called as structured light method. (Macy 2015, p. 2490.) The basic idea of the triangulation can be seen in figure 19.

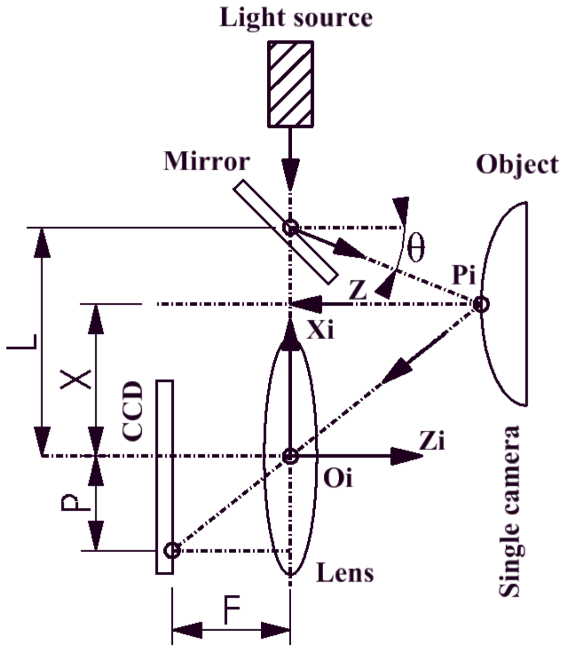

Figure 19. Basics of triangulation method by using single CCD camera (Raja & Fernandes 2008, p. 38).

The commercial equipment presents first bigger and more expensive scanning technology, which can scan objects up to 0.05% from the scan size, which means up to 0.05mm resolution. These are usually industrial level equipment, which can function automatically equipped with automatic turntable for 360˚ scans. (David 2016.) The smaller, hand-held devices, which reaches resolution of 0.9mm, offer fast and easy way to scan the objects into usable 3D model (3D Systems 2016). Examples of these can be seen in figure 20.

Figure 20. Examples of commercial 3D scanners (David 2016 & 3D systems 2016).

3.3 Software

Scanning process produces information in a form of point-cloud that needs to be post processed. This means that the noise in the point cloud will be reduced and the number of the points are decreased. (Raja & Fernandes 2008, p. 22-23.) Other defects in the information present themselves as inaccuracies in alignment of the point clouds and issues concerning fitting the surfaces and segmentation (Kovács, Várady & Salvi 2015, p. 44).

The objective is to produce a point cloud that is cleaned from unnecessary information and merged possibly to other scans. The result is a format, which can be used in generating useful CAD model. In this stage, the information from the point cloud is generated into surfaces, which can be presented as CAD model. This process is done via separate software, which can be found from several distributors in commercial format. (Raja & Fernandes 2008, p. 22-23.)

3.4 Applications

The applications of 3D scanning are part of the reverse engineering process and it includes always some existing part or object that is scanned and transformed eventually into CAD format (Raja & Fernandes 2008, p. 16). The common product development process as seen in figure 21 presents the cycle in which 3D scanning can be seen as a part of the process.

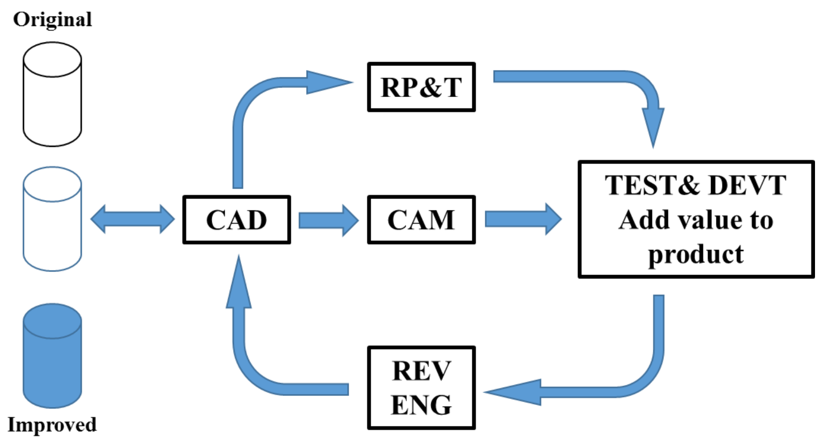

Figure 21. Typical product development cycle (Raja & Fernandes 2008, p. 16).

Examples of the technology can be found anywhere where the physical form is transformed into digital form such as automotive body design in which a small-scale model of a car in scanned and the information is used to refine the body design of the car (Raja & Fernandes 2008, p. 154). The principle of the body design process is presented in figure 22.

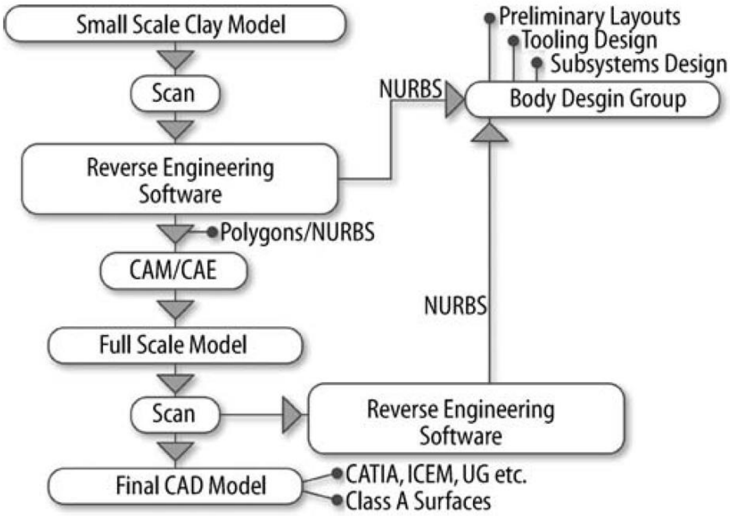

Figure 22. Example of using 3D scan in car body design (Raja & Fernandes 2008, p. 154).

3D scanning can also be used in investigating an existing part and improving it according to the requirements of application. For example, a die cast of aluminum can deform in the casting process due to heat and the cast needs to be machined after the casting. In addition, the mold made out of metal can deform in the process. In this case, 3D scanning can be used to measure the cast after die-casting and the received information is then compared into the original CAD data for both the aluminum cast and the metal mold. This way right correction procedures can be determined for the mold because machining product after the casting process increases costs and prolongs the manufacturing time and is therefore undesired. (Seno et al. 2014, p. 96-97.) Example of the original cad data and scanned data after die-casting can be seen in figure 23 and the correcting procedure in figure 24.

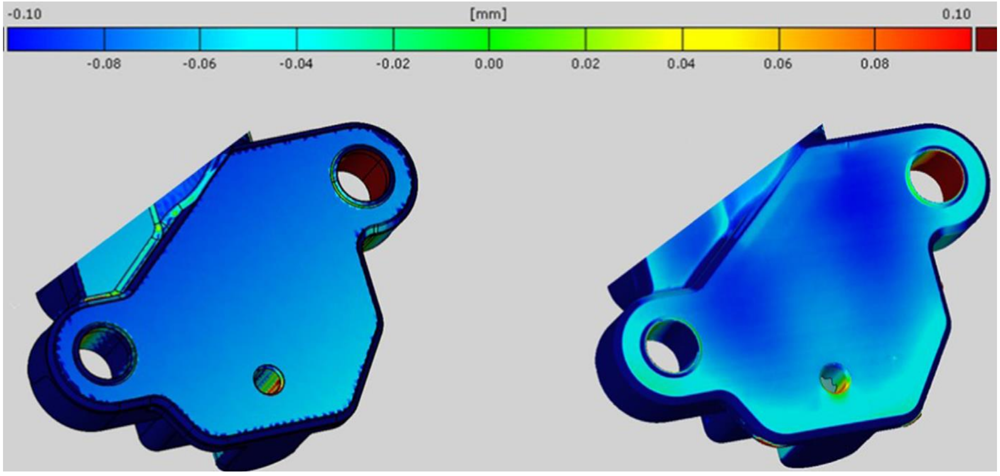

Figure 23. Example of comparing original CAD data to a scan (Seno et al. 2014, p. 97).

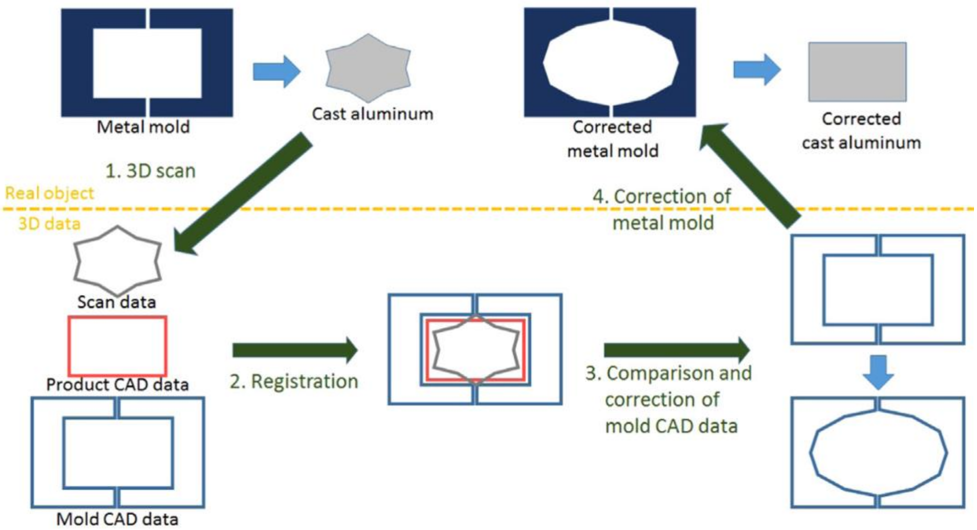

Figure 24. Process of mold correction (Seno et al. 2014, p. 97).

4 ENGINEERING DESIGN AND AM

Engineering design is a process, which refines different product specifications into a product, which is designed according to customer needs. The process is divided into different stages, which take information as an input, and produces decisions according to the information. Performed actions are based on synthesis, analysis and evaluation, which are part of the main factors in the process. (Kamrani & Nasr 2010, p. 8-9.) The process consists on the following parts according to Kamrani & Nasr (2010, p. 8-9):

1. Identifying the problem or customer need.
2. Study of the problem.
3. Producing solutions.
4. Selecting the most suitable solution.
5. Making a prototype from the solution.

Engineering design can also be seen as a part of larger concept in which technology and social aspects and sections of society meet according to figure 25 (Pahl et al. 2007, p. 20).

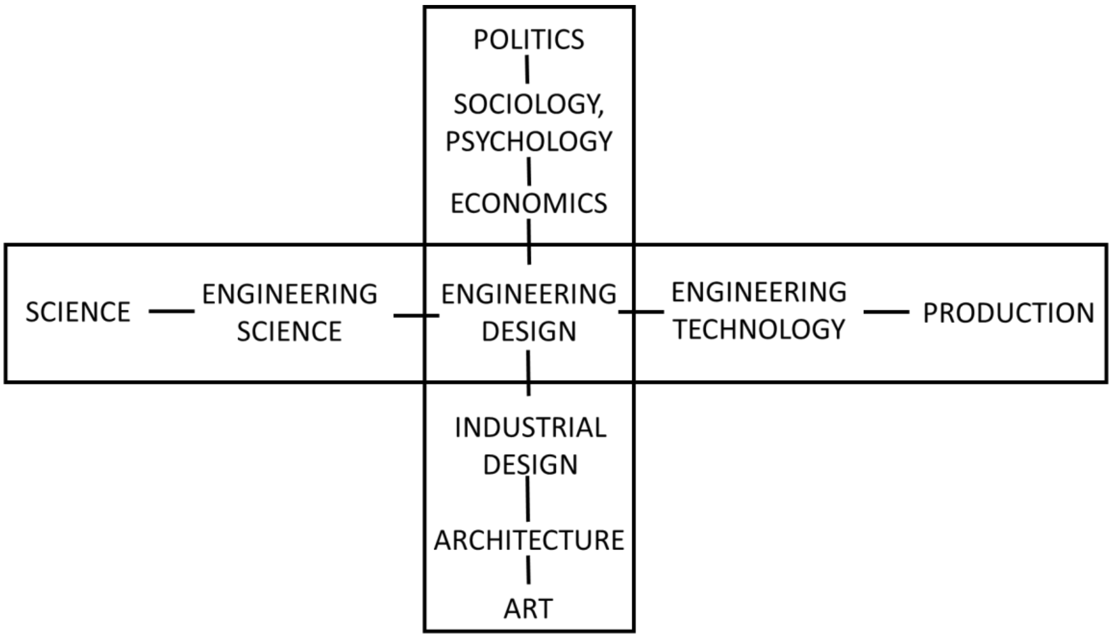

Figure 25. Engineering design at the center (Pahl et al. 2007, p. 20).

The design process is connected to actions, which aims to produce the mechanics, outlook and material selections of a functional product. If the process is taken into a broader perspective, the term product development is used. This encloses the whole process from recognizing market opportunities to production and selling the product. (Kamrani & Nasr 2010, p. 34-35.)

The generic product development process is presented in figure 26 and the design part of the process shows at what stage the design work is needed in the whole development process (Ulrich & Eppinger 2008, p. 23).

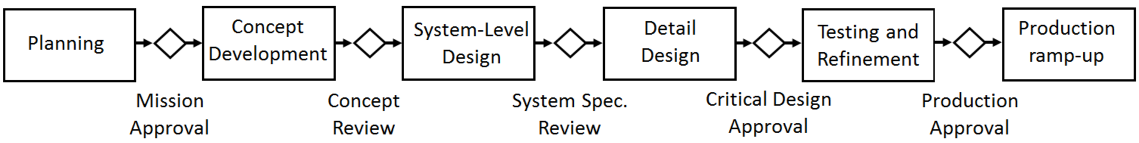

Figure 26. Generic product development process (Ulrich & Eppinger 2008, p. 23).

In planning phase, the markets are defined, technologies are investigated and assessed and the base for manufacturing is started. In concept development, customer needs are collected, design concepts are developed and manufacturing costs and production processes are evaluated. System-level design phase produces targets for marketing, produces the basic architecture for the product and incorporates industrial design to the process and the final idea for product assembly is determined. In detail design phase marketing plan is produced, detailed structure and geometry for the product is created including material selection and the planning for production methods is made. Testing and refinement phase tests the product and its qualities with prototypes, manufacturing personnel are familiarized to production. In the final phase, production ramp-up, the production is started. (Ulrich & Eppinger 2008, p. 14.)

4.1 Industrial design and engineering design

In order for the whole product design process to be successful, the collaboration between two design strategies, engineering and industrial design, is needed. Industrial design process concentrates on the usability, looks and maintainability of the product (Ulrich & Eppinger 2008, p. 190). Engineering design process ensures functionality and reliability of the product also in a technical level (Pahl et al. 2007, p. 19). The difference and position of the two approaches can be seen in figure 27.

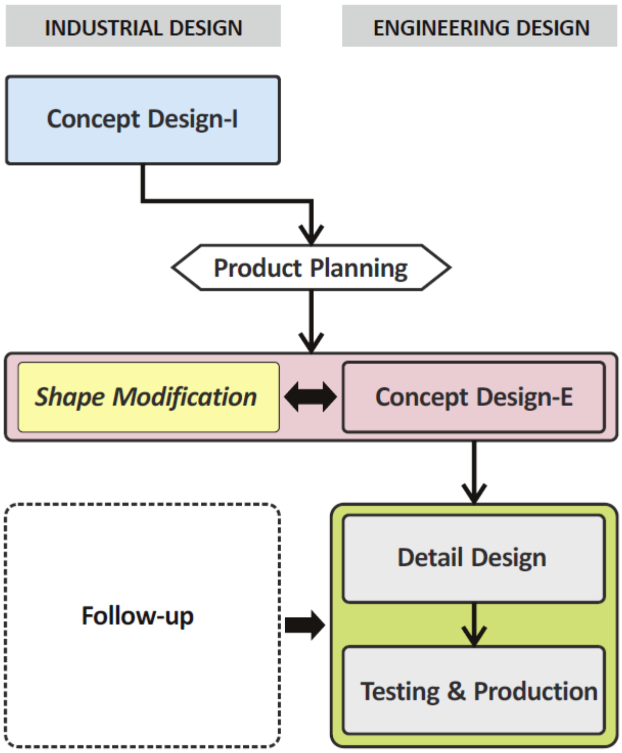

Figure 27. Generic product development process (Kim & Lee 2016, p. 241).

When investigating the possibilities of 3D CAD in the design process, it offers the possibility to investigate the product in realistic form and use it as a virtual prototype for testing product characteristics in a concept level. For actual prototype creation, rapid prototyping (additive manufacturing) gives the possibility to turn 3D CAD model into realistic and testable product. (Ulrich & Eppinger 2008, p. 257-258.) In the industrial design process, conceptualization phase gives the form and outlook to the product for evaluation purposes. The concept is then refined in order to select the final concept by making actual model from the product. This is made by using actual materials like plastic, wood or foam. Functions from the product can be added to the model for testing actual product features like moving product parts. This stage in considered expensive when calculating the costs of a single real model. (Ulrich & Eppinger 2008, p. 199.)

4.2 DFAM – Design for additive manufacturing

Traditional concept for designing products for manufacturing point of view is being added a new perspective. AM technology provides the possibility to incorporate the design process easily to manufacturing at low-cost principle and enabling manufacturing process with small quantity for products and giving certain freedom for the design process to create something that is usually not possible to do in traditional DFM (design for manufacturing) process. Possibility to retailor the conventional manufacturing process with AM produces different kind of design method. (Gibson et al. 2015, p. 399-400.)

DFAM is a concept, which covers all the AM processes, and it investigates the relationship between design work and AM production technology (Thompson et al. 2016, p. 737, 740). DFAM can be divided into two sections. The first offers new design possibilities in which rules for traditional manufacturing can be disregarded. There is no need for acquiring tools for production and designing the forms are no longer manufacturing method dependent. Immediate design changes can be made without affecting to the manufacturing time and costs. All the possibilities of the product can be liberated. The second section consists of rules for DFAM. These rules include issues that have to be taken into consideration when designing for AM. (Stratasys direct manufacturing 2014, p. 1-9). According to Stratasys direct manufacturing (2014, p. 1-9), these rules and restrictions can be divided into categories when using FDM printing:

1. Quality and accuracy of the STL file.
2. Layer thickness and width in the extrusion process.
3. Wall thickness of the part.
4. Required support structure according to form.
5. Threads in part.
6. Creating an assembly.

4.3 Combining the design process and AM

Additive manufacturing can be integrated to the design process in three different phases: making conceptual models, confirming the fitting of the parts and using the printed part for prototype purposes. Concept modeling is usually done in 3D CAD environment but AM gives better opportunity to assess and understand the design. (Hanssen et al. 2015, p. 2518-2519.) AM is especially useful in improving the concept by replacing traditional soft models fabricated from foam or hard models fabricated from e.g. wood or plastic (Ulrich & Eppinger 2008, p. 198).

Assemblies, which have parts that are fitted together, can be modeled with CAD and the functionality of the fitting can even be tested virtually. The reality is usually different with tolerances in the manufacturing and the user experience behind the actual assembly work. AM offers a flexible way to make the assembly and even changing and iterating the variables in the design. (Hanssen et al. 2015, p. 2520.)

Prototypes gives important information about the product. According to Ulrich & Eppinger (2008, p. 250) prototypes are used for "learning, communication, integration and milestones". Designer can learn the functionality of a product with a prototype, prototype can be used in giving information to the project management and other parties, the complete assembly can be integrated together and find out the total functionality and last, prototypes can act as a mark of reaching certain milestones in the product design process. (Ulrich & Eppinger 2008, p. 251-252.) At this stage, the changes in the design are undesirable but the need remains. Need for quick changes is possible with AM without need to change the actual production tooling or -process. (Hanssen et al. 2015, p. 2521.)

4.4 DFAM process models

Additive manufacturing methods have been developing rapidly over the past years but the design process for AM has not been developed the same way yet. The AM processes have been investigated and documented quite well but the design process is missing an established process chart, which would take the special needs of AM into account. One of the most important and first things to be taken into consideration while creating a DFAM process is to map the manufacturing abilities of different AM technologies and also constraints such as heat deposition and accessibility constraints like nozzle position and speed of material deposition. This is the key for modifying the engineering design process for AM purposes. (Vayre, Vignat & Villeneuve 2012, p. 632.) Nevertheless, some design process charts have been investigated and developed from different research works.

Vayre et al. (2012, p. 634-637) presents a design process model in figure 28, which is divided into four steps:

1. Analysis of the part specifications; material selection, behavior of the material according to purpose and resolving volume for adding material.
2. Proposal of rough shape/shapes for the part; creating the first shape through optimizing the topology automatically and including the AM constraints and possibilities or using the designer expertise or design guidelines.
3. Optimization of the shape/shapes according to the specifications and constraints for manufacturing; minimizing the volume of the part by using FEA (finite element simulation) and taking the specific behavior of the part into account

   Validation of the design proposal; definition of the residual parameters for manufacturing, validation of the part through virtual manufacturing.

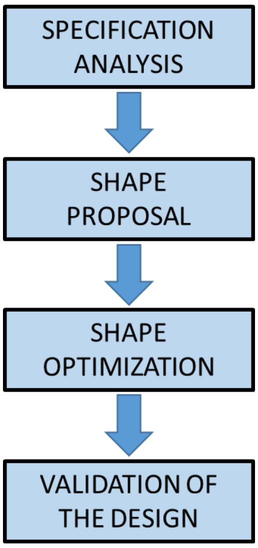

Figure 28. DFAM process chart according to Vayre et al. (2012, p. 634-637).

The design process can also be integrated with expertise from the manufacturer side. This kind of method emphasizes free communication and information flow in the DFAM process. (Hovilehto et al. 2016, p. 2.) The integrated DFAM model is presented in figure 29.

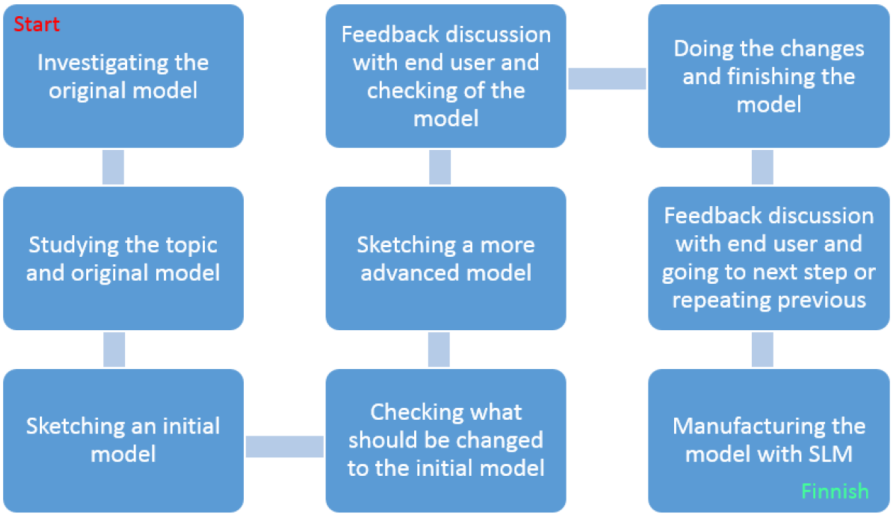

Figure 29. DFAM process chart according to Hovilehto et al. (2016, p. 2).

The DFAM process starts with investigating and studying the original model, which exists already. The model is used to create a preliminary sketch, which takes the rules for AM into consideration. This model is then taken into an iterative process for improvement in which the end user gives comments about the functionality. Main purpose in this stage is to reduce used material and weight and also reduce the manufacturing time. This then leads to final model, which is also commented by the end user for final comments and improvements, and eventually the model goes into the manufacturing phase. (Hovilehto et al. 2016, p. 2-4.)

Design methodology can also be divided into two different sections which represent the process of designing shapes for AM. Process-driven approach includes the AM capability to create almost impossible shapes by optimizing part topology. This is done by using different algorithms and codes, which reduce the freedom in the part geometry. This includes the usage of FEA and understanding of part utilization as a ready and fabricated part. Designer-driven approach emphasizes human experience and knowledge in creating shapes. This includes the information flow between the designer and AM fabricator. (Hällgren, Pejryd & Ekengren 2016, p. 247.) The process can be divided into stages as follows according to Hällgren et al. (2016, p. 247):

1. Selecting the build direction.
2. Taking surfaces that has to be post-machined into account.
3. Optimize the geometry according the need for supports.
4. Improving the probability of success by interacting with the AM fabricator.

5. Integration of parts that do not move into one if they consist of same material.
6. Reducing part volume to decrease the build time.

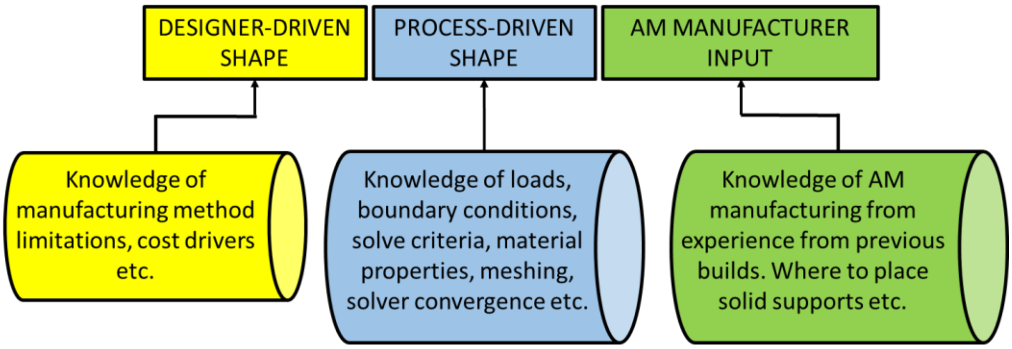

Figure 30. Separation of the design methods (Hällgren et al. 2016, p. 2).

Fourth model to be presented incorporates the environmental aspect to additive manufacturing. The freedom in design work has a great impact on the sustainability of the product. The main environmental views in additive manufacturing are usually based on basic LCA (life-cycle assessment) through the design process and therefore a new perspective is required. (Tang, Mak & Zhao 2016, p. 1562.) Figure 31 presents a model, which incorporates the environmental evaluation model to AM from design point of view.

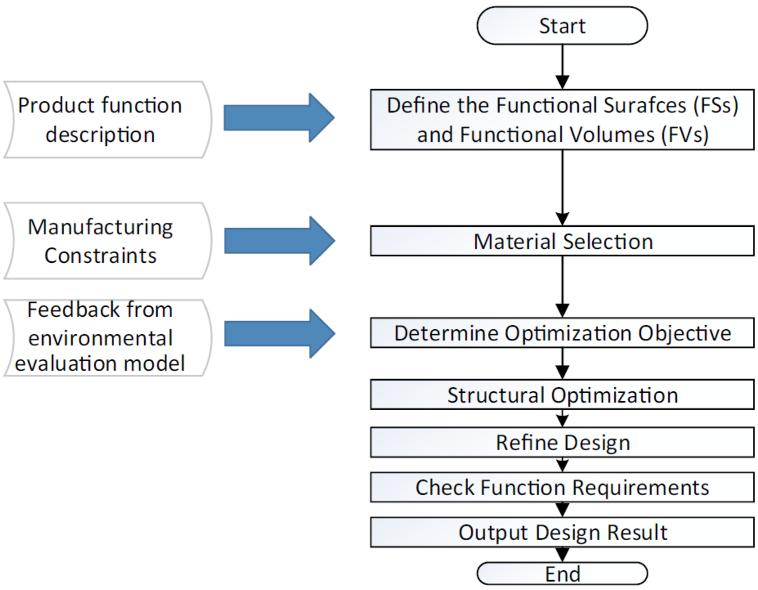

Figure 31. Sustainable design for AM (Tang et al. 2016, p. 1562).

The model is based on the usage of freedom of design, which takes the environmental effect of the product into consideration as feedback. In the model, the functional surfaces and volumes gives fulfills the desired function of the product. This information come from the initial product idea in the design process. In the material selection stage, a material which has the lowest possible environmental impact and which can fulfill the needs of the functional surfaces and volumes is selected. Then the product will be optimized according to the feedback from environmental evaluation model, which includes the sustainability of the AM process such as consumption of material and energy. This will lead to the finished design through optimization stages and finally into fabrication which produces a product that is updated to be more environmentally friendly. (Tang et al. 2016, p. 1562.)

5 LEARNING ENVIRONMENT

Main purpose for engineering education is to produce learning which allows students to transform into engineers who possess sufficient knowledge to act in a technological environment. This confronts students to different kind of systems, products and processes. As they learn to become engineers, they have to be technologically aware, consider social responsibility and be innovative. This requires an environment in which these aspects integrate into learning. (Crawley et al. 2014, p. 17-18.)

5.1 Basics of learning environment

Learning environment is a combination of places or spaces, different equipments and the way to operate which makes learning possible and promotes it. The combination of learning and using the environment has to be planned according to pedagogical and didactical principles. One of the most important thing is to make efficient learning possible and produce good learning outcomes. (Koramo 2012, p. 6.) Learning in the environment should be student-oriented and it combines many different dimensions together such as physical appearance, virtual spacing, personal being and -skills and social environment and interaction (Kankaanranta, Mikkonen & Vähähyyppä 2012, p. 5). Structure of basic learning environment is presented in figure 32.

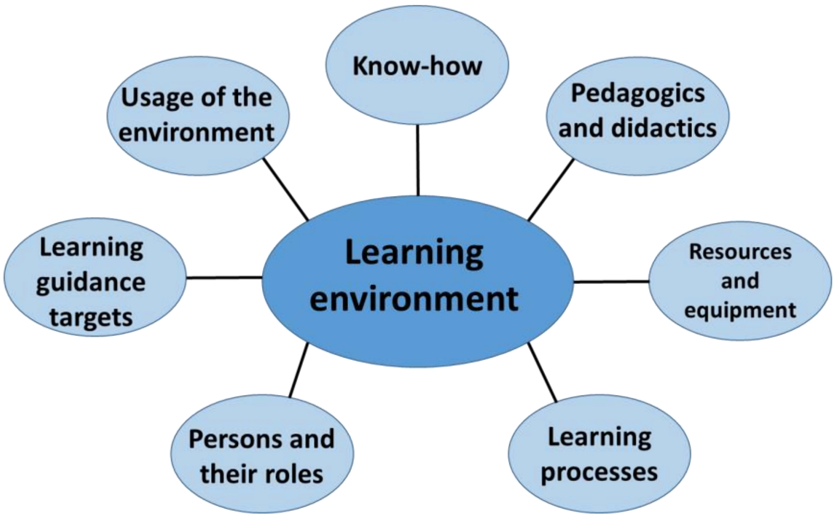

Figure 32. Structure of a learning environment (Frisk 2010, p. 7).

Basic structure of a learning environment can be based on an open or closed principle. Open learning environment starts from the student and the needs for learning, it puts the learning process itself as a priority, it integrates actual work situations to learning situations and it utilizes learning methods that look the traditional methods from whole new perspective. Openness means also that the student has to take responsibility from the learning outcome and use self-guidance during the learning process. Closed learning environment is almost the opposite; it emphasizes the teacher input to learning and the contents of the education itself. (Frisk 2010, p. 6.)

5.2 CDIO principle

CDIO (conceive-design-implement-operate) iniative was founded in 1997 in MIT and it was born from the need to renew engineering education to meet requirements from real life engineering applications and companies. The creation of the iniative started from mapping skills needed in engineering and this was done by forming a committee consisting members from industry, companies, different engineering units and academic institutes. This produced the first version of the CDIO Syllabus, which acts as the map for educating engineers according to demands set by the technological society. CDIO forms a framework, which can be used in engineering school or university as a guideline to be incorporated to their curricular plan work. (CDIO Iniative 2016a & CDIO Iniative 2016b) The logo for the iniative is presented in figure 33.

Figure 33. CDIO iniative logo (CDIO Iniative 2016a).

The CDIO approach to engineering education comes from the principle of Conceive, design, implement and operate. According to Crawley et al. (2014, p. 7) the approach has three main goals:

1. ” Master a deeper working knowledge of technical fundamentals
2. Lead in the creation and operation of new products, processes and systems

3. Understand the importance and strategic impact of research and technological development of society."

The CDIO principle can also be seen as a lifecycle model for a product or process, which is the typical target for an engineer to work with (Crawley et al. 2014, p. 27). The application of the principle lifecycle to engineering can be seen in figure 34.

Conceive		Design		Implement		Operate	
Mission	**Conceptual Design**	**Preliminary Design**	**Detailed Design**	**Element Creation**	**Systems' Integration & Test**	**Lifecycle Support**	**Evolution**
• Business Strategy • Technology Strategy • Customer Needs • Goals • Competitors • Program Plan • Business Plan	• Requirements • Function • Concepts • Technology • Architecture • Platform Plan • Market Positioning • Regulation • Supplier Plan • Commitment	• Requirements Allocation • Model Development • System Analysis • System Decomposition • Interface Specifications	• Element Design • Requirements Verification • Failure & Contingency Analysis • Validated Design	• Hardware Manufacturing • Software Coding • Sourcing • Element Testing • Element Refinement	• System Integration • System Test • Refinement • Certification • Implementation Ramp-up • Delivery	• Sales & Distribution • Operations • Logistics • Customer Support • Maintenance & Repair • Recycling • Upgrading	• System Improvement • Product Family Expansion • Retirement

Figure 34. CDIO as a lifecycle model (Crawley et al. 2014, p. 27).

The approach consists of two basic elements, which have been created to make sure that the program works. The first is to identify the different needs, which are essential to learning, the second is to create a learning process, which has stages to ensure that the needs from the first part are met. From these two elements, the CDIO Syllabus and CDIO standards have been created. (Crawley et al. 2014, p. 7.) The CDIO syllabus offers a model for engineering education, which produces desired learning outcomes according to the principle (CDIO Iniative 2016d). The CDIO standards gives a description of the program and they consist of 12 different standards for giving guidelines and principles for constructing the education (CDIO Iniative 2016c). Implementation of the approach is presented in figure 35. The standards are as follows according to CDIO Iniative (2016c) and Crawley et al. (2014, p. 36.):

1. Principle of Conceive – Design – Implement – Operate; context of the program.
2. Learning outcomes which the program produces.
3. Integrated curriculum; CDIO skills structured to the curriculum.
4. Orientation and introduction to engineering; a course which gives basic idea from engineering.

5. Design and implement projects; students go through projects which start from designing and lead to the implementation of the solution.
6. Learning environments; actual learning environments in which the students can work according to the principle.
7. Learning experiences that are integrated; combining skills and knowledge in learning.
8. Active methods for learning and teaching; passive transfer of information is replaced by active learning based on participation and gaining experiences from learning.
9. Developing the staff CDIO skills; the staff are able to act according to the principles and practices.
10. Developing the teachers CDIO skills; teacher is able to work according to the principles and enable the learning experiences for the students.
11. Assessment of the CDIO skills; developing and usage of assessment methods for measuring the learning of the student.
12. Evaluation of the degree program which uses CDIO; degree which uses CDIO can develop the CDIO teaching and implementation in the academic program.

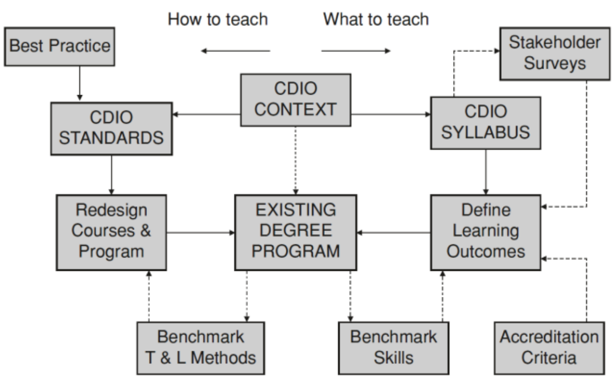

Figure 35. Implementation of the approach (Crawley et al. 2014, p. 35).

5.3 CDIO and additive manufacturing – example

The CDIO principle suits also for a product innovation projects, which are done in collaboration with industry. RPS (rapid prototyping service) is an example from a working model in which the CDIO principle in an academic institute and real life company work together. The RPS model is integrated to the academic environment via CDIO principle in which the students can learn the principles of AM and also techniques from company processes and services. The RPS model consists of four elements: teamwork, the CDIO principle of the degree program, a product and the collaboration with a company. (Tenhunen & Aarnio 2010, p. 11.) Principle of the model is presented in figure 36.

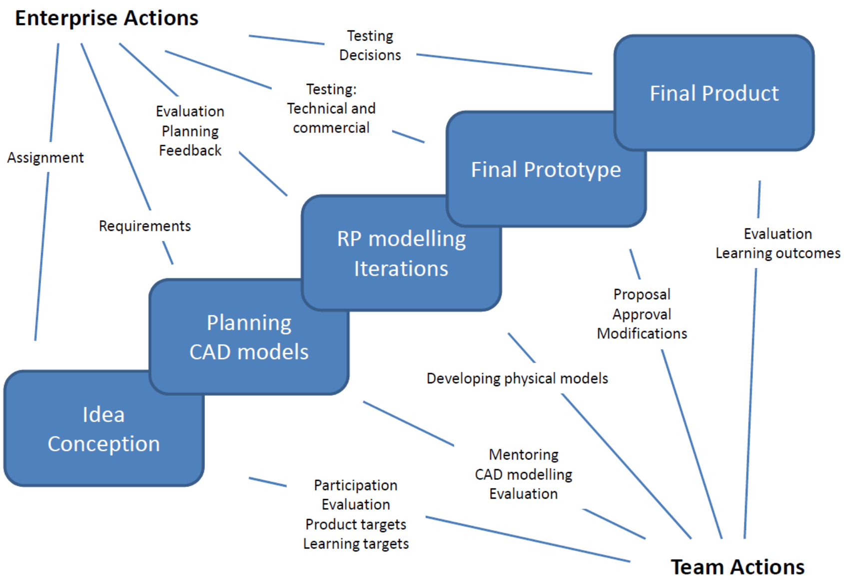

Figure 36. RPS-model (Tenhunen & Aarnio 2010, p. 11).

The integration of the model to the CDIO is based on listing different objects, which represent nouns, and actions, which represent verbs (Tenhunen & Aarnio 2010, p. 38). The listings are presented in table 2.

Table 2. Listing of the objects and actions of RPS model (Tenhunen & Aarnio 2010, p. 38).

THE LIST OF OBJECTS (NOUNS) WILL INCLUDE FOLLOWING:	THE LIST OF ACTIONS (VERBS) WILL INCLUDE FOLLOWING:
• The RP team (including students and experts) • The customer and its agents • The target product and its properties • The RP technique chosen • The Prototype • The time schedule and the budget	• Discussing the task and choosing the innovation level • Regulating and adjusting the RP process during work • Changing, Developing and Iterating the Prototype • Testing the prototype solutions • Finishing the best prototype • Saving the necessary CAD documents • Consulting and Advising by experts • Learning to conceive, design, implement and operate the RP process by the students • Making decisions by the customers

These listings form the basis of the model, which separates three different processes that run together. The industry innovation projects are based on product development model

(Tenhunen & Aarnio 2010, p. 13.) Model can be seen as a tighter format in figure 37, which contains the three processes.

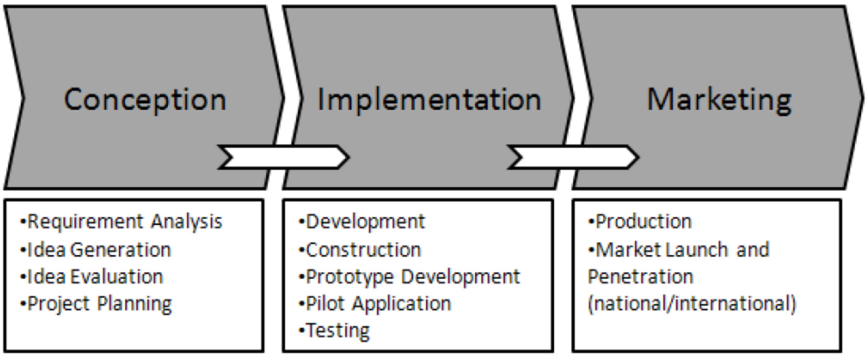

Figure 37. Industry innovation process model (Tenhunen & Aarnio 2010, p. 13).

The three processes come together with CDIO principle as a cycle consisting of the stages of CDIO and also the industry product development model stages (Tenhunen & Aarnio 2010, p. 39). The cycle model is presented in figure 38.

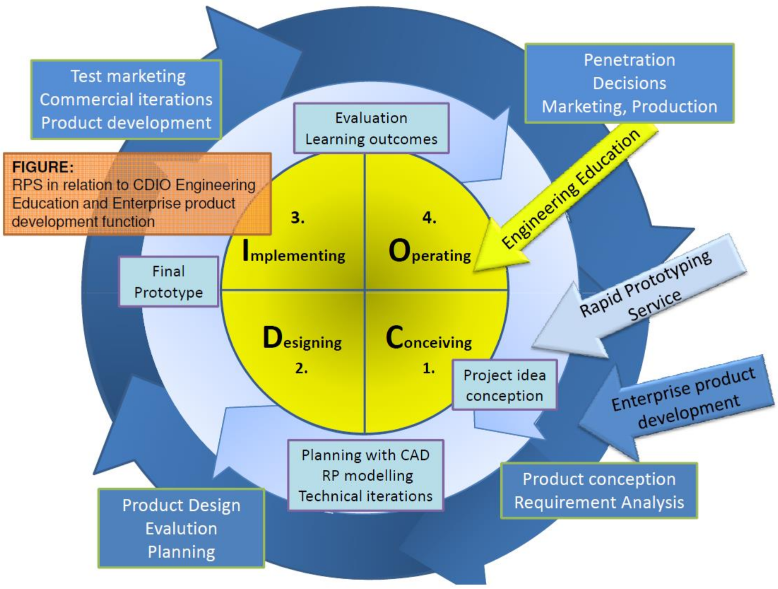

Figure 38. Cycle of the RPS/CDIO model (Tenhunen & Aarnio 2010, p. 39).

This model gives the students the opportunity to learn AM technology, understand the basic principle of engineering work as a service process and also get to know the business side of engineering via the development of a product. This kind of model in engineering education produces engineers who have competent technical skills, are able to work in a social environment and are resourceful in entrepreneur skills. (Tenhunen & Aarnio 2010, p. 48).

6 REVIEW OF EXISTING PRINTING ENVIRONMENTS AND PROJECTS

Learning in different printing environments gives view to applications that are used in real-life situations. Students are able to apply the acquired knowledge in different areas such as engineering, aerospace, health care and different scientific applications. Equipment in the environment enables students to build their own learning outcome and even courage them to pursue entrepreneurial future through up-to-date 3D-printing equipment. (Stratasys 2016a.) Environments provide situations in which student experience technology through problem solving and therefore receive more knowledge than in theoretical situations (Horvath 2014, p. 152).

6.1 3D Boosti and 3D Invest project in Tampere, Finland

Three educational units, Tampere University of technology (TTY), Tampere University of applied sciences (TAMK) and Sastamala municipal education and training consortium (SASKY) in Tampere, Finland are building a 3D printing concentration which goal is to develop learning environments and improve the competitiveness of companies, which are dealing with additive manufacturing technologies. The learning environments are developed to educational purposes and they are done in collaboration with companies. The project includes equipment acquisitions to the three educational units and the goal is to increase AM knowledge thru the usage of the equipment. Companies can collaborate with the educational units in different projects and therefore use the equipment in AM experiments to increase their own knowledge in the business. (TAMK 2016c.)

The project is divided into two initiatives, 3D boosti and 3D Invest. 3D boosti (1.10.2014 – 30.6.2017) consists of applying funding from EAKR to create a network of experts within AM, fortify the collaboration between universities, educational unit and companies, participating to international network, acquiring information about AM and developing the learning environments within AM. (EAKR 2014). 3D Invest (1.3.2015 – 30.6.2017) consists of the definition of the technical specifications and details of the equipment, acquirement of the equipment and introduction to the equipment. This includes the designing and building of different environments for R&D and innovation. Total budget for both projects in over 1000000€. (EAKR 2015.)

6.1.1 Tampere University of technology environment

TTY part of the project consists of acquisition of the following equipment according to 3D Pirkanmaa TTY (2016):

- 1pcs Lithoz CeraFab 7500 (Technology: Photopolymer VAT)
- 1pcs Direct energy deposition equipment, built on existing robot cell (Technology: DED, CMT – Cold metal transfer).

The university has also an environment called TUTLab, which is based on the FabLab-concept developed in MIT. The lab works as concentration of education in which the students can learn to use digital fabrication by doing different works and by solving problems. (TUTLab 2016.) According to TUTLab (2016), the lab has the following equipment:

- 1pcs Minifactory Innovator (Technology: FDM)
- 2pcs Projet 460Plus (Technology: material jetting)
- 1pcs 3D scanner Artec Eva.

The students of the university can also use 3D printers, which are located in the university library. The library has two FDM printers manufactured by Prenta and the students can reserve time for printing from electronical calendar. Printing itself is free of charge and the students can learn and develop the AM knowledge alto outside the formal lecture hours. (TUT library 2016.)

The university has also a club called Pullonkaula, which is formed by the students from modern production technology degree. The club has developed a printer capable printing objects from chocolate. They have also developed a modular, delta structured 3D printer, which has changeable extruder capable extruding different materials like plastic or ceramic. (TTY Pullonkaula 2016.)

6.1.2 Tampere University of applied sciences environment

TAMK part of the project consists of acquisition of the following equipment according to 3D Pirkanmaa TAMK (2016):

- Stratasys Objet350 Connex3 (technology: PolyJet)
- powder bed fusion (PBF) printer for metals; not defined, will be acquired fall 2016.

The university has already existing 3D printer, which locates in the mechanical engineering laboratory. The printer is used mainly for product development purposes in which the printed part is used for viewing features of the product. University uses the equipment also within normal laboratory services for outside customers. (TAMK 2016b.) The laboratory has the following equipment according to TAMK (2016b):

- Stratasys Elite 3D (technology: FDM).

TAMK has already some existing equipment, which are used in AM course and student hobby activities (Surma-Aho 2016). Example of course is Basics of Rapid Prototyping, which is held for mechanical engineering students (TAMK 2016a). According to TAMK (2016a), the main learning outcomes for the course are:

- Understanding the basics of additive manufacturing.
- Understanding of 3D-printing process, limitations and possibilities.
- Basics of designing for 3D-printing.

The course consists of lectures and exercises. The evaluation of the course is based on project work, different exercises, exam and student activity. The project work is based on designing an assembly, which has different features such as holes, threads and different thicknesses. Important thing is that it has moving parts. (Surma-Aho 2016.)

6.1.3 Sastamala municipal education and training consortium environment

SASKY part of the project consists of acquisition of the following equipment according to 3D Pirkanmaa SASKY (2016):

- Stratasys Fortus 360mc (technology: FDM).

SASKY offers a vocational college level degree in 3D printing and modeling in which the student will graduate as an artisan of the area. The degree length is 3 years. (SASKY 2016.) Main areas of the degree according to SASKY (2016) are:

- Manufacturing prototypes and different product.
- Defining the features of the printed part.
- Machining the fabricated parts with hand tools and automated tools.
- Usage of 3D modeling.

6.2 University of Virginia Rapid prototyping lab

Department of Mechanical and Aerospace Engineering in University of Virginia has built a rapid prototyping laboratory, which gathers CAD work and 3D printing with FDM and PolyJet together. Goal is to provide education and services not only to the school personnel and students but also to clients outside the school. Laboratory has even priced the lab work for outside customers. (University of Virginia 2016a.)

According to University of Virginia (2016b), the laboratory has the following equipment as seen in figure 39:

- 8 pcs Stratasys uPrint Plus (Technology: FDM)
- 1pcs Stratasys FORTUS 400 (Technology: FDM
  1pcs Stratasys Objet Connex 500 (Technology: PolyJet).

Figure 39. UVA Rapid prototyping lab (Makezine magazine 2016).

From the point of education, the goal is to give a real life environment for engineering students in which they can produce parts from 2D CAD drawings. This gives them a new perspective in investigating mechanisms and components. This gives easier approach to engineering to the new students and gives them a view to engineering in real life. The university has taken new kind of pedagogical approach to engineering by giving students learning by doing alternative instead of applied or abstract courses which may seem to theoretical. The university has integrated the lab to learning by focusing really on what is important for students to experience and visualize the problem instead of theoretical approach. They even influence to the attitude of the engineering students in order to give them better understanding of their own future as engineers. (University of Virginia 2016a.)

6.2.1 Applications of the University of Virginia printing laboratory

According to University of Virginia (2016a), the main applications of the laboratory concentrate on engineering education purposes and client works. Main areas of application in engineering education are:

- student workspace for personal projects
- idea hatchery; turning ideas into reality
- cross-degree usage; for example for electrical engineering students are able to build electrical components.

According to University of Virginia (2016a), the main areas of application for outside operators are:

- cross-usage for other schools of the university (for example Environmental science school)
- Stratasys Ltd; University acts as educational advisor for the printer manufacturer
- collaboration with companies such as Lockheed Martin and Airbus in product development area.

6.3 Fachhochschule Technikum Wien (FHTW), Austria

University of Applied Sciences Technikum Wien situates in Vienna, Austria and it provides 13 Bachelor degrees and 18 Master degrees in the areas such as mechanical engineering, electronic engineering, mechatronics and urban renewable energy technologies (Fachhochschule Technikum Wien 2016b). The university has about 4000 students and the education has scientific background but it also focuses learning by practice. The university collaborates with the business and industry sector, which gives work and practice possibilities to the students. University was founded in 1994 and it was given the status of university of applied sciences in 2000. (Fachhochschule Technikum Wien 2016a.) The degree in mechanical engineering has a 3D-printing laboratory, which concentrates to plastic printing (Kollegger 2016). The laboratory can be seen in figures 40 and 41.

Figure 40. FHTW 3D printing laboratory.

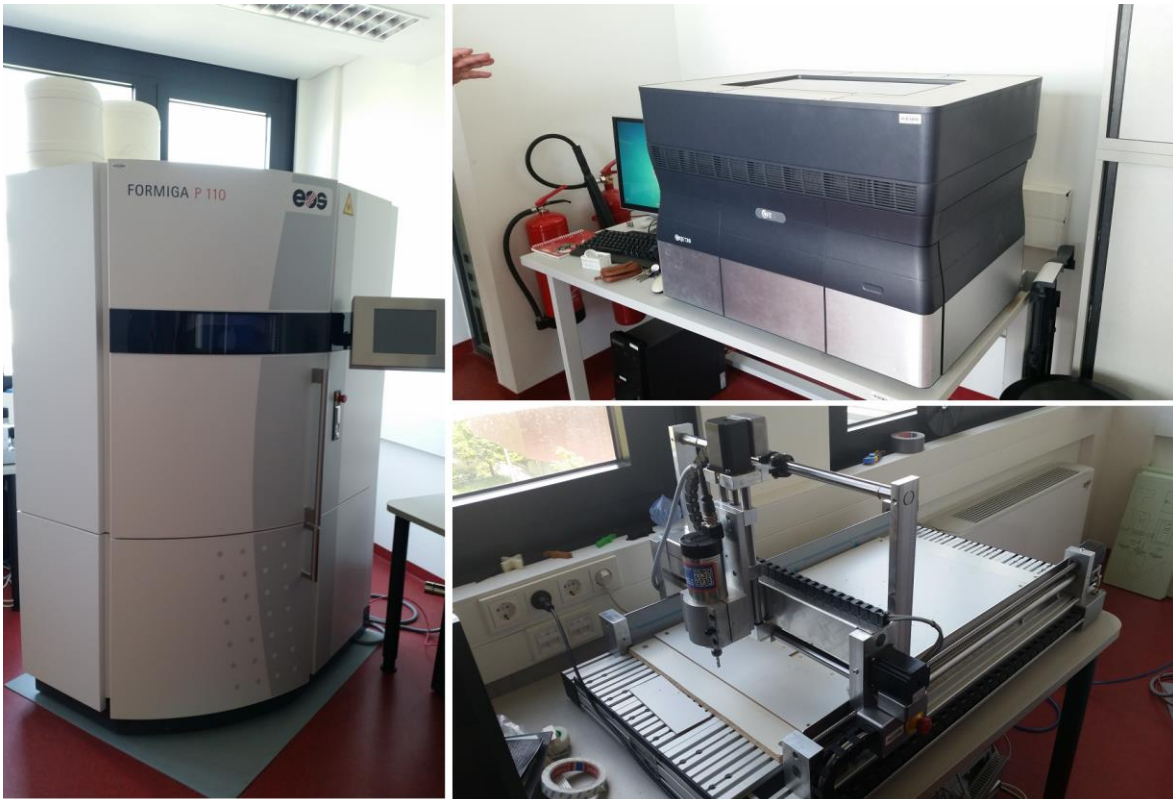

Figure 41. FHTW 3D printing laboratory equipment.

According to Kollegger (2016), the laboratory has all the equipment in one space and a computer for handling 3D-models and STL-files. The laboratory has the following equipment:

- MakerBot Replicator (Technology: FDM)
- Dremel Idea Builder (Technology: FDM)
- Stratasys Objet 30 (Technology: PolyJet)
- EOS Formiga P110 (Technology: SLS)
- washing station for Objet

- modular unpacking and Sieving station for EOS Formiga
- Eder blasting equipment (glass).

6.3.1 Example of 3D-printing learning assignment in FHTW

Principle of teaching and learning 3D printing is that the students will work with each printing equipment learning its function, specifications and application. The teacher gives an orientation lecture to the technology and the student model a part in his/hers own time and produces a printable STL-file. The file will then be printed in each equipment and the results are compared. The group will be kept small (max. 10 students) so that the learning is as efficient as possible. During the comparison of the results, possible changes will be determined and the 3D-model will be altered and printed again. (Kollegger 2016.) Principle of the example can be seen in figure 42.

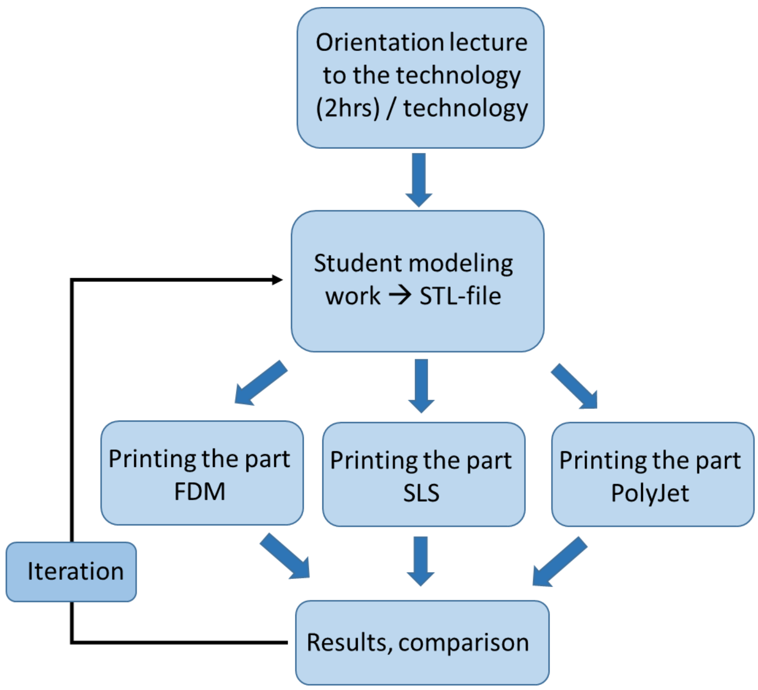

Figure 42. Example of a learning assignment (Kollegger 2016).

Other example from a learning assignment is that the teacher gives first 15 hours of lectures about the technology. Then other 15 hours of lectures will be used in presenting the equipment and the usage. Teacher shows already printed part to the students and they have to determine how to manufacture the part without printing. Then the alternative manufacturing method will be compared to the printing method according to manufacturing time. (Kollegger 2016.) Principle of the example can be seen in figure 43.

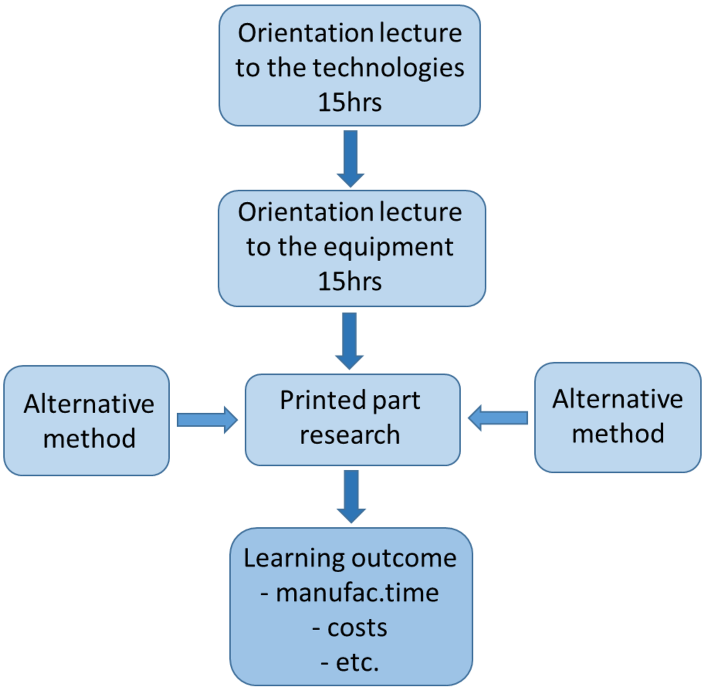

Figure 43. Example of a learning assignment (Kollegger 2016).

7 3D PRINTING EQUIPMENT – LAPLAND UAS

A decision was made in spring 2016 in the LUAS unit of technology to acquire basic equipment for 3D printing and –scanning. Idea was to use Finnish manufacturer for gaining more practical technical support and easier warranty issues. Purpose was also to support Finnish 3D-printing industry and their development. After comparisons, company called Minifactory Oy Ltd, was selected as a distributor. Big advantage was that the company has a Kampus in their website, which contains information about the introduction, usage, and maintenance in video format (linked to YouTube) and the instructions cover all the necessary information for introduction and using the printers. This simplifies the presentation of the equipment to the students since they are now able to learn the equipment by themselves starting from the installation of the necessary software. The equipment uses FDM technology since it presented to be the most reasonable choice for starting the introduction of 3D printing.

7.1 Technical details

The acquisition consisted of six printers and the two main types can be seen in figure 44:

- 2pcs Minifactory Innovator
- 2pcs Minifactory Education 3 single extruder

  2pcs Minifactory Education 3 dual extruder.

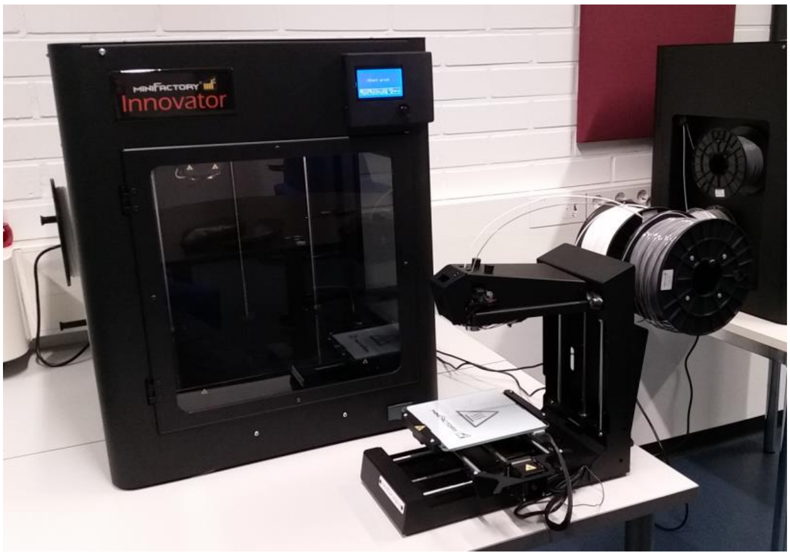

Figure 44. Minifactory Innovator L and Education 3 Dual extruder.

The Education 3 single and dual extruder model are exactly same besides the amount of nozzles in the extrusion head (Minifactory 2016b). The technical details of the printers can be seen in table 3.

Table 3. Technical details of the printers (Minifactory 2016a, Minifactory 2016b).

	Innovator L	Education 3 Dual	Education 3 single
Technology	FDM	FDM	FDM
Dimensions	530x560x670mm	440x295x340mm	440x295x340mm
Weight	45kg	12kg	12kg
Structure	Metal casing, ball screws, servo motors	Metal casing, ball screws, step motors	Metal casing, ball screws, step motors
Printing materials	PLA, ABS, Nylon, PEEK, PVA, carbon fibre (PLA), graphene (PLA), PC	PLA, ABS, Nylon, T-glase, Laywood, Polycarbonate, Bendlay, HIPS, PET, TPE, PVE, HPDE	PLA, ABS, Nylon, T-glase, Laywood, Polycarbonate, Bendlay, HIPS, PET, TPE, PVE, HPDE
Printing area	330x260x310mm	150x150x150mm	150x150x150mm
Amount of printing heads	2	2	1
Resolution	0.02 - 0.40mm	0.1 - 0.35mm	0.1 - 0.35mm
Wall thickness	min. 0.4mm	min. 0.4mm	min. 0.4mm
Layer thickness	0.02 - 0.64mm	0.02 - 0.64mm	0.02 - 0.64mm
Filament diameter	1.75mm	1.75mm	1.75mm
Nozzle	0.4 - 1.75mm	0.4 - 1.75mm	0.4 - 1.75mm
Max. extruder temperature	390°C	290°C	290°C
Max. platform temperature	125°C	90°C	90°C
Position precision (X/Y)	0.01mm	Not announced	Not announced
Position precision (Z)	0.02mm	Not announced	Not announced
Dimensional accuracy	±0.2mm	Not announced	Not announced
Max. Printing speed	60mm/s	80mm/s	80mm/s
Heated printing chamber	YES	NO	NO
Chamber temperature	Max 55°C	NO	NO
Filtration	YES (act.carb.fib + HEPA)	NO	NO
Data transfer	USB	USB Cable + computer	USB Cable + computer
Software	Repetier Host	Repetier Host	Repetier Host
Power consumption	150 - 350W, max. 600W	120W	120W

7.2 Introduction of the technology

The equipment arrived to the school in fall 2016. The deal included a one-day introduction course in which Minifactory representative kept on-site course concerning the printers. Teachers who are responsible for CAD/AM-teaching attended to the course and it covered everything from starting the print work to the maintenance of the equipment. Soon it was noticed that mastering the equipment requires many hours doing printing and it would be an ongoing process together with the students.

7.3 Operation and software

The operation of the printers requires a software called Repetier-Host for Minifactory, which has been optimized just for Minifactory in collaboration with the software developer (Repetier / Hot-World GmbH & Co. KG). The usage of the software is fully covered in the Minifactory Kampus by videos. The printing software is used for controlling the completely 3D printing and the basic functions are according to figure 45:

- adjusting the printable object (scaling and size, multiple prints, placement etc.)
- settings of the printer (printable area size, movement speeds, connection settings etc.)
- settings of the printing event (printing speed, filament settings, adhesion type, support structures etc.)
- calibration (for Education 3 calibration is done via the software, for Innovator the calibration is done via the equipment, software is not needed)

  slicing of the STL-file and settings for it (software uses CuraEngine or Slic3r in slicing).

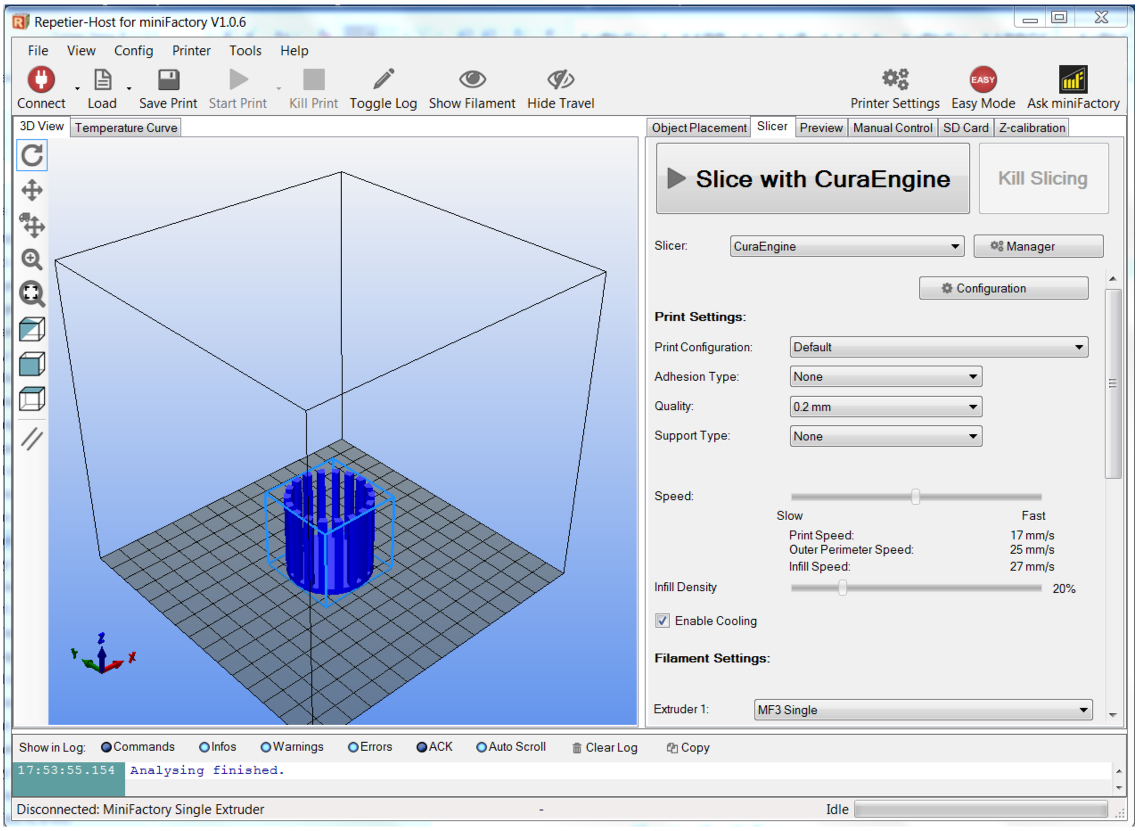

Figure 45. User interface of Repetier-Host for Minifactory.

Basic principle of the operation of the printers is same than in other FDM printers. After the generation of the necessary g-code with the software, the user transfers it to the printer. In Innovator, g-code produced by Repetier-Host is transferred by USB-stick so the printer can work independently while in Education 3 the printer requires active connection to the computer via USB-cable.

The basic phases for using the printers are derived from the generic AM-process as follows. This will be used in introducing the printing process to the students as seen in figure 46:

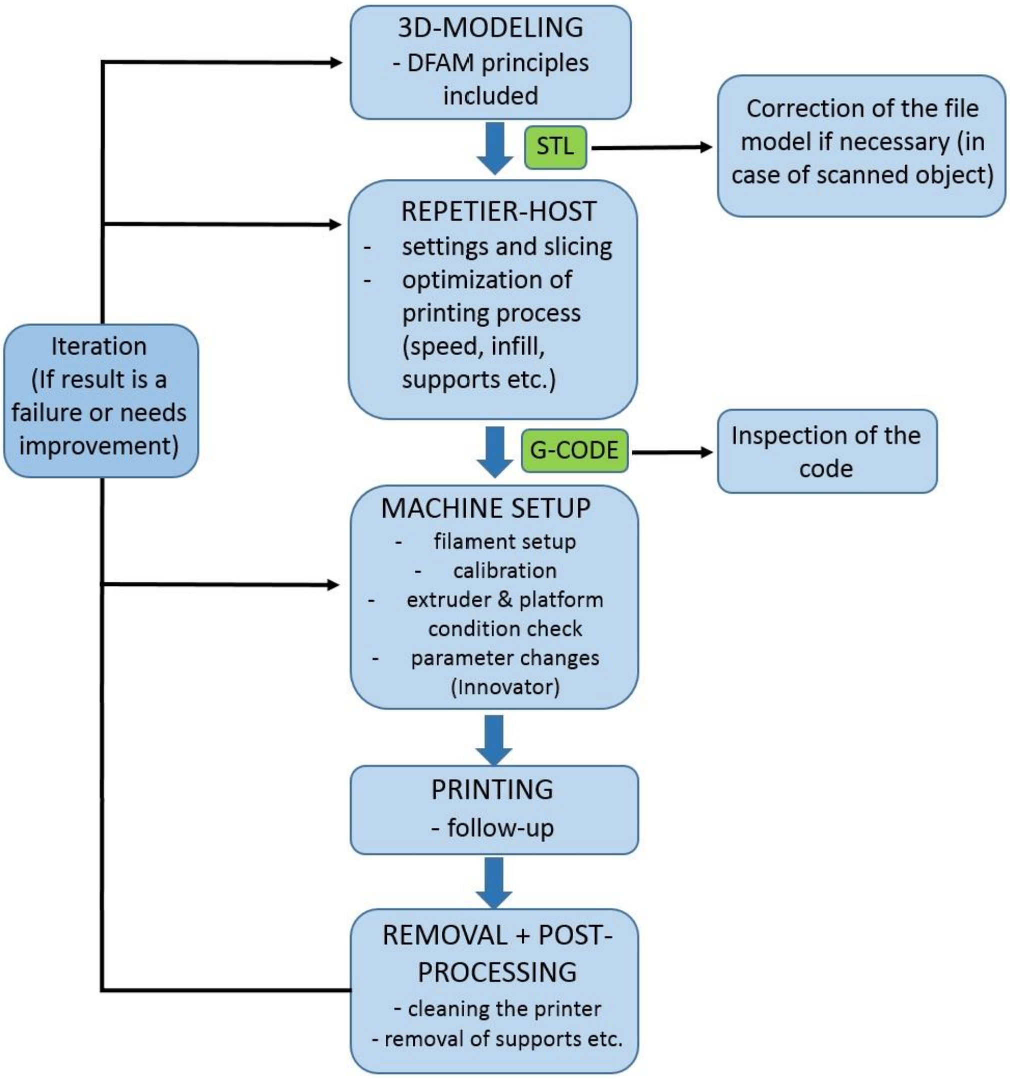

Figure 46. Simplified 3D printing process chart for the students.

The process model presents the necessary phases for performing the print from technical point of view. It contains also the possible improvement of scanned file (point cloud) since there is usually the need for clean or improve the scan result. This can be done with the scanner software of by external software. The process chart includes all the important stages and the iteration if the result is a failure or it needs to be improvement. This also works as the model for improving your print and the student can define what the necessary stage to be returned to is (iteration).

Operation of Education printer is done through the software and the printer itself do not have any displays or control devices (calibration, start printing etc.). Operation of Innovator is done via the display panel and control knob, which is presented in figure 47.

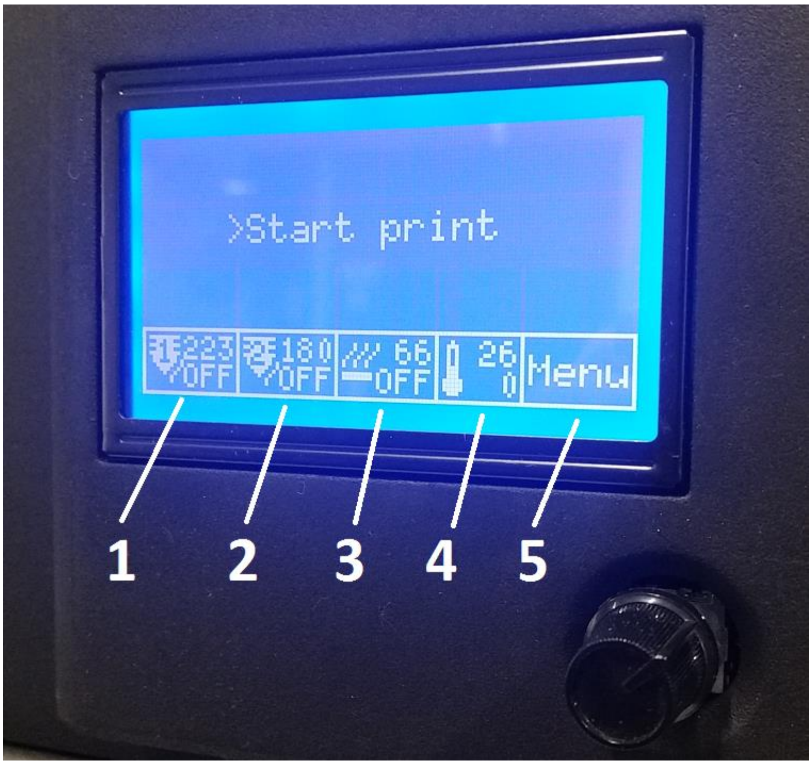

Figure 47. Innovator L control display and -knob.

The Start print command reveals different alternatives for printing and at the bottom of the display user can see the pre-set temperatures according to selected filament material. By selecting desired material (PLA, ABS, Nylon or PC) the machine uses pre-set temperatures for nozzles, bed and chamber, which can be seen in the control display. User can change these values by selecting them. The information according to figure 47 are as follows:

1. extruder 1 (left) temperature
2. extruder 2 (right) temperature

3. bed temperature
4. chamber temperature
5. menu; reveals more options / while printing: extruder fan on/off.

The command tree for specifying the operation of the printer can be revealed from the Menu-option. The structure of the command tree can be seen in figure 48.

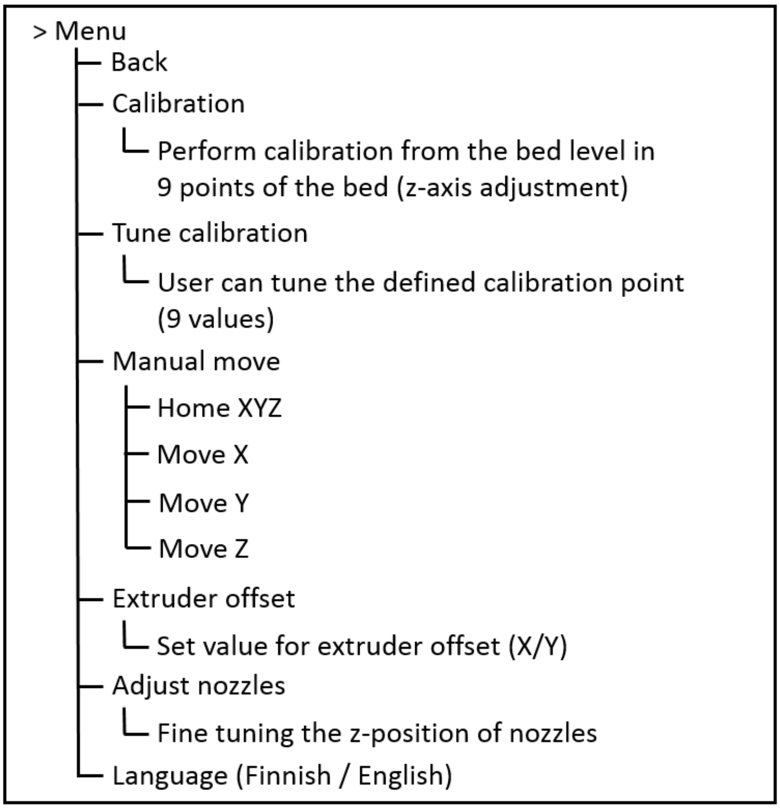

Figure 48. Innovator L Menu-option command tree.

The command tree for the actual printing event can be revealed from the Start print-option. The structure of the command tree can be seen in figure 49.

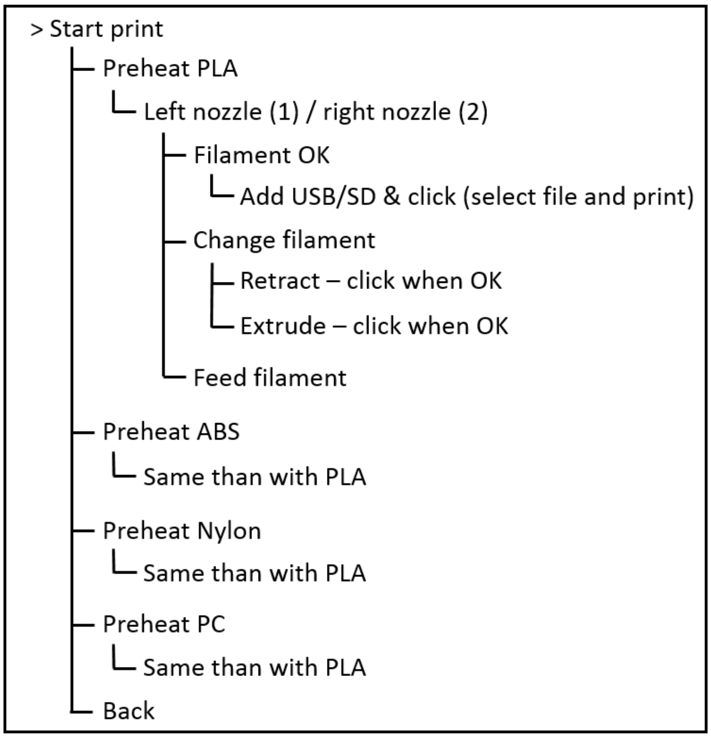

Figure 49. Innovator L Start print-option command tree.

7.4 Maintenance

Maintenance of the equipment is important keeping the equipment fully functional. Main areas for the maintenance are defined by the manufacturer and detailed instruction videos are found from the Kampus on the company website. The main topics of the maintenance are (Minifactory 2016c):

- Keeping the equipment clean
    - wiping dust with microfiber cloth
    - removing print residues (filament)
- Storage
    - storage in dust-free environment
      room temperature (not in cold storage)
- Lubrication on linear guidance bars
    - cleaning the bars with microfiber cloth
    - lubrication of bars with oil/grease (meant for bearings and linear systems)
- Checking electrical wires
    - check the condition of the wires
    - if broken, contact Minifactory

    - check that the wires are able to move freely during printing
- Cleaning and changing nozzle
    - keeping the nozzle area clean, cleaning with copper brush
    - changing the nozzle
    - cleaning the nozzle in acetone
    - opening the nozzle hole with needle etc. thin object
- Extruder head
    - cleaning the pinch/idler rolls with a brush
- Cleaning the platform
    - removing the glass platform
    - washing the glass
    - applying new layer of coating (glue).

7.5 Design of a test part

First step in introducing the equipment and technology is get to know the features of the equipment and the performance. FDM technology offers many freedoms for the designer but also some limitations when considering the DFAM principle. A test part was designed and printed for this reason. The students are able to see the possibilities and limitations of FDM technology with the help of the part. There is already different test parts available on the internet but by designing own test part just the desired features can be studied. This part offers the basic features and further investigations can be made by the students themselves.

The following presents the selected features that will be included in the test piece printed with PLA material. Test part size is 200 x 200 x 5 mm, which can be seen in figure 50.

- wall thickness (0.2 / 0.4 / 0.6 / 0.8 / 1.0 / 2.0 mm)
- holes in horizontal position, for accuracy (0.5 / 1.0 / 1.5 / 2.0 / 3.0 / 5.0 mm)
- holes in vertical position, for overhangs and accuracy (1.0 / 3.0 / 5.0 / 8.0 / 12.0 / 20.0 mm)
- angles without support, for overhangs (from platform level: 20 / 30 / 45 / 60 degrees)
- horizontal faces without support, for overhanging faces(span of 10 / 20 / 30 / 45 / 60 mm)

- shaft-hole-pair, presentation of the minimum space between parts (spacing of 0.3 / 0.5 / 0.8 / 1.0 / 1.2 / 1.5 mm)
- fillets with different radiuses and text options (text font arial, height 5.0 mm, extrusion 1.2 mm).

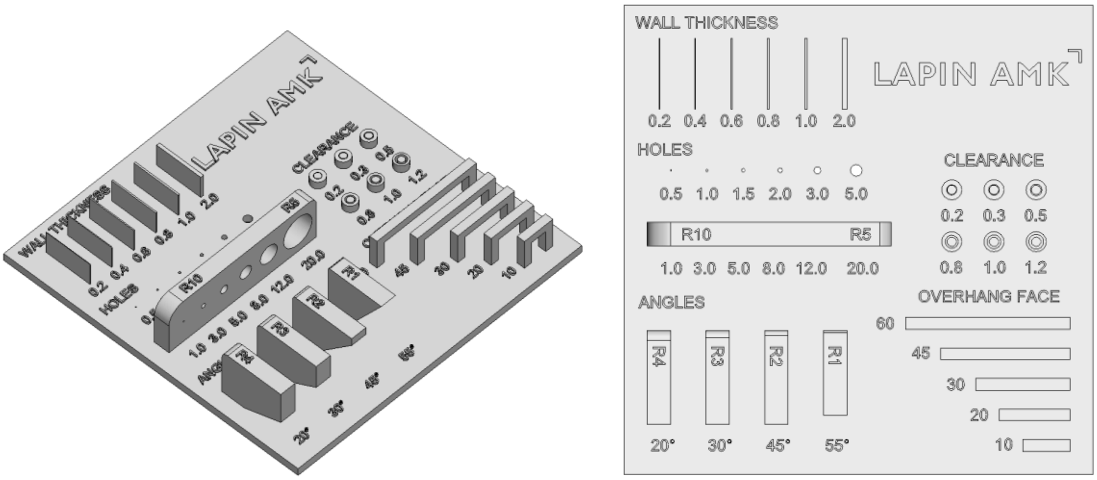

Figure 50. Test part with different features.

7.6 Results from the test part

Test part was printed with 38 mm/s speed and with 20 % infill rate. The printing time was 16 hours and 28 minutes. The following presents the main conclusions from the print:

- Wall thickness: 0.2 and 0.4 mm were not printed, from 0.6 mm forward print was successful. This was a surprise since the manufacturer promises minimum of 0.4 mm wall thickness with 0.4 mm nozzle diameter. This requires further tests with different specification values for the printing.
- Holes in horizontal position: holes 1.0 – 5.0 mm were successful, holes 8.0 – 20.0 mm presented some overhang on top of the hole.
- Holes in vertical position: 0.5 mm hole was not successful, 1.0 mm was barely successful and it need some post-processing, holes 1.5 – 5.0 mm were successful. Smaller holes require post-processing to open them up.
- Angles without support: angles 45° and 55° were successful, angles 20° and 30° presented some overhanging in the downward tapered surface.
- Horizontal faces without support: these were surprisingly well printed, only the span of 60mm presented some hanging filament.
- Shaft-hole-pair: clearance of 0.2 mm was not successful, 0.3 mm barely successful, 0.5 – 1.2 mm were successful.

- Fillets and text options: fillets from 1.0 mm forward were successful and the text also.

The results of the print can be seen in figures 51 and 52.

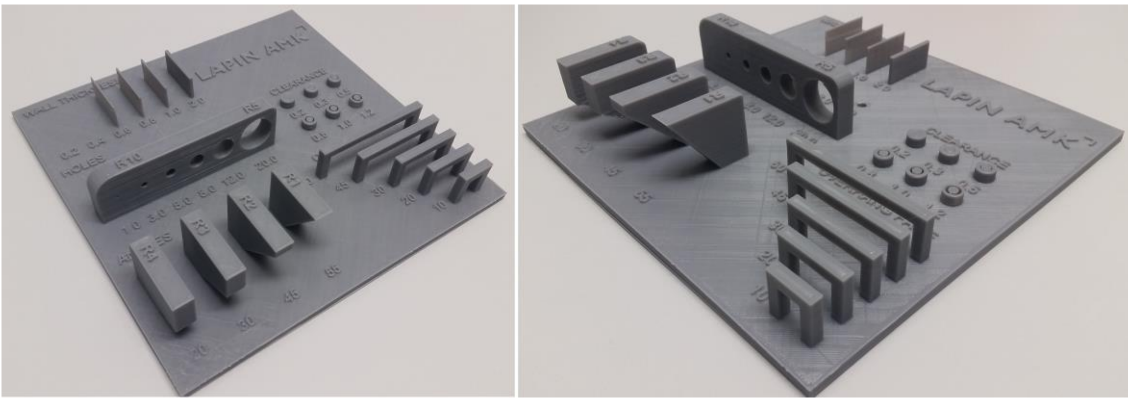

Figure 51. General views from the print.

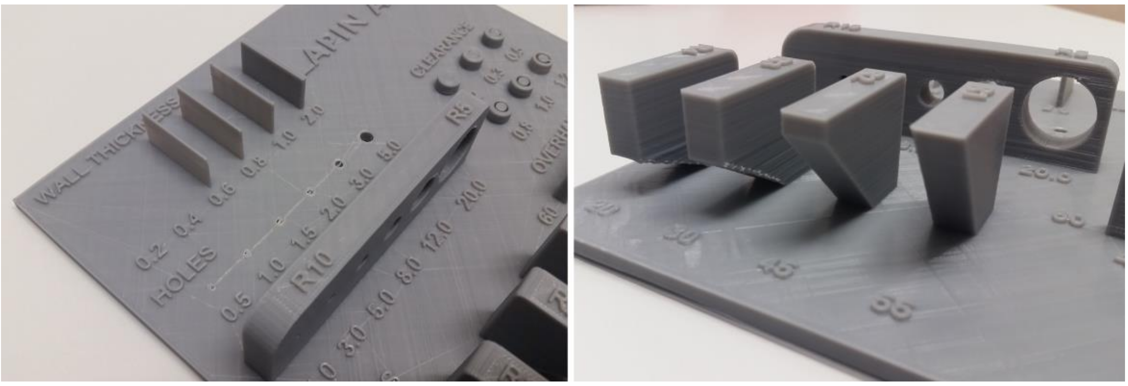

Figure 52. Detailed views from the print.

Overall the results met well the values from literature, especially the 45 degree rule and the vertical hole diameter limitation. This was just one test and the result can be improved by affecting to the printing factors. This test did not include the tolerances in the dimensions but generally, the 0.5mm tolerance limit can be seen well in the clearances in which the 0.5 test succeeded well. The testing piece will give good insight to the students about the capabilities of FDM technology and encourage them to pursue their own tests with the technology.

8 3D SCANNING EQUIPMENT – LAPLAND UAS

3D scanning is an important addition to the AM learning environment and it provides way to use reverse engineering and re-design desired objects. Aim was to acquire basic scanning equipment and get to know the technology and its possibilities. The scanning is presented in this section as a part of the environment in a basic level.

8.1 Technical details

The acquired equipment was DAVID Starter-Kit 2. The scanner is able to scan fine surface details in <0,2mm accuracy. The starter kit consists of following equipment, which can be seen in figure 53.

- 2 megapixel webcam, high resolution (Full HD), auto-focus
- webcam stand (tripod, adjustable)
- red line laser module (Class 1, wavelength 650 nm), adjustable focus
- panels for calibration (maximum object size 400mm)
- installation plate for calibration panel
- DAVID scanner software.

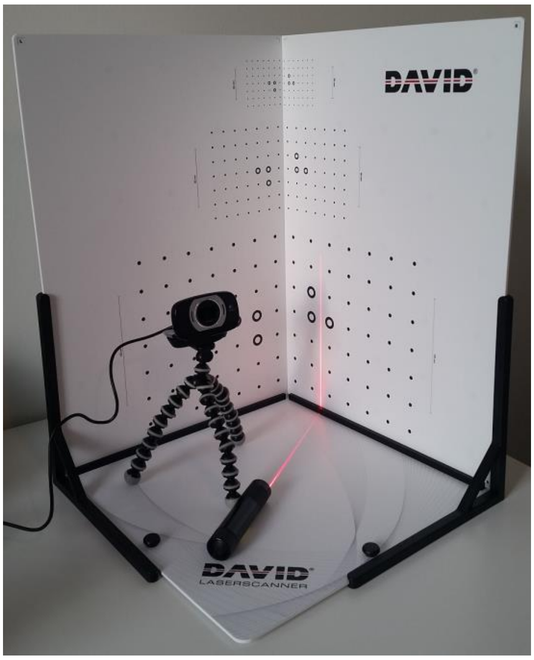

Figure 53. DAVID Starter kit-2 equipment.

8.2 Operation

Scanning takes place in the calibration corner with the panels. It is recommended to use some kind of stand under the scanned object so that the camera is able to read also the calibration panel markings. Object size is according to the panel, maximum size is ~400mm (depending on the shape). The equipment can scan only one side at a time and the object must be turned between scans so that multiple scans cover the whole object.

The process of the scan can be divided into stages as follows and the scanning event can be seen in figure 54:

1. Calibration of the camera through DAVID software.
2. Placing object to the center of the panels.
3. Sweep the object with laser; multiple sweeps collect more data.
4. Webcam reads the laser line and software creates point cloud (obj-file).
5. Object is turned as many times as needed for 360° scan.
6. The scans are fused together in the software.
7. The scan can be post processed in the software (improve quality, fill in voids etc.).

Figure 54. View from the scanning event.

8.3 Suitability for student design projects

The scanner is optimal choice for table-size working and it suits well for scanning small objects. Scanning is suitable topic for student development work and the phases of the work are quite simple yet the processing of the scans require work. Here are some preliminary topics and applications for attaching scanning as a part of the AM process. These can be used later as a reference while planning exercises and tasks:

- Attaching existing parts to a separate design: scanning an object and adding the model to an existing 3D model done with CAD.
- Inspecting the features of existing part: measurements, geometry etc.; This can be used as an exercise for comparing the accuracy of the scanner or different scanners.
- Modifying scanned part: modifying the scanned model file.
- Reverse engineering: copying existing part through scanning and printing. The possibility to re-engineer the part.

Preliminary tests with DAVID starter kit 2 proved that the scanning process is quite sensitive to ambient light so it has to be adjusted so that the software is able to read the data. Handling 360-degree scan with multiple scan results requires fusion in the software. This presented also as a challenge in the beginning, therefore mastering the software is must in order to use the device.

For future development, a live scanner such as DAVID SLS (structured light scanner) with turntable or handheld live-scanner would be a good choice since they enable the scanning process at once. Even then, the result requires post-processing for AM purposes with software meant for modifying scans.

9 CREATING LEARNING ENVIRONMENT

The main part of this thesis is to present the plan for creating learning environment that combines the fundamentals of engineering design (mechanical engineering design tasks and the theory behind them) and additive manufacturing. This requires the combination of theory and practice and new kind of operational models to teaching and learning. 3D printing can be used in so many ways in education so therefore it is important to find efficient methods for the merging of the ideologies.

9.1 Active learning in AM – groundwork to learning environment

The traditional teaching leans usually heavily on lecturing while the students listen. This does not work when there is real-life problems to be solved in learning and the modern direction is to make students to participate actively to learning. Best results are achieved by combining theory and practice. This is also one of the basic ideologies of CDIO approach, which are used in creating the learning environment. Figure 55 presents the aspects (and challenges) of active learning and it is used as a foundation while planning the learning environment.

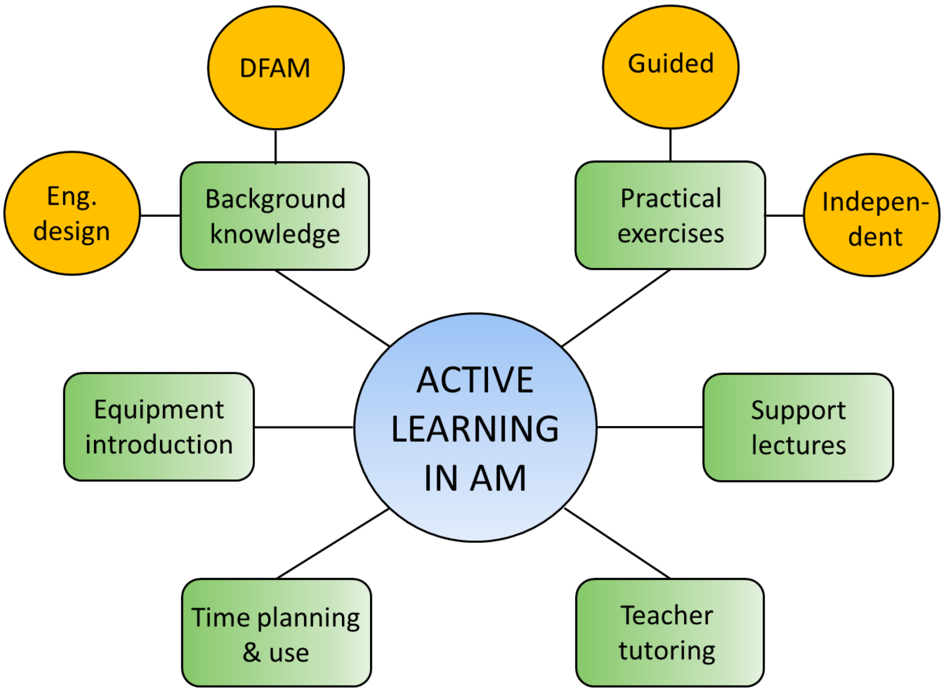

Figure 55. Components of active learning.

9.2 AM learning environment ground plan

The ground plan for the environment is under development while writing this part. The equipment are situated in a separate room, which is not fully equipped for 3D-printing purposes. An initiative in LUAS has been made for developing new environments for mechanical engineering degree and one part is building the AM laboratory. The following presents the basic ideas and requirements for the environments space. This information in then used in construction planning:

- The environment must be situated right next to the CAD laboratory; the AM laboratory is accessible through door between the laboratories and also from the hallway. This ensures fluent transition from one space to another. The door must muffle the sound coming from the printers so that they will not disturb CAD teaching and working.
- The laboratory must be accessible through access control system in which the students use e.g. personal security card for independent laboratory working without surveillance. This way the users can be monitored in the environment when there is no lecturer or personnel present.
- Sufficient space has to be reserved also for future acquirement of other printing technologies (e.g. SLA with necessary extra equipment).
- The laboratory must include space for work desks and storage space/cabinets for tools, printed parts etc.
- There must be separate air removal spots for printing equipment, which produce dangerous fumes (e.g. while printing ABS with the Education 3 model).
- The ventilation on the laboratory must be sufficient.
- The laboratory must be equipped with sufficient fire warning and –extinction system.
- Surveillance system via webcam will be installed for monitoring the printers via internet. A circuit breaker will be included in the system and it is remote usable.
- The laboratory must be equipped with possibility to wash e.g. building platforms.

9.3 Working in the environment – guidelines and safety

3D-printing laboratory is relatively safe compare e.g. to electrical engineering laboratories. Most of the rules are connected to working with the printer of to the post-processing phase.

The following presents the main guidelines for safe working according to the current situation. More safety rules must be included to the laboratory working instructions if other printing technologies are acquired later.

- Person working in the laboratory must go through a basic training about using the equipment including safety issues.
- Main safety guidelines provided by the manufacturer must be followed.
- Beware of the hot parts of the printer such as the nozzle and thermistor.
- Innovator: do not open the printer door during printing, wait for the fans to have ventilated the fumes from the printer. Avoid unnecessary staying close to the printers while printing.
- Education 3: avoid unnecessary staying close to the printers while printing.
- Use the ventilation equipment provided while printing.
- Do not touch the printer during printing and beware of the moving parts.
- Always use access control system when working in the laboratory independently.
- Perform possible post-processing according to general safety rules while using tools and sharp objects. Use safety goggles if post-processing includes the danger of flying objects (e.g. grinding).

The safety orientation will be included in the equipment introduction for safer working in the environment. A student, who will be working in the laboratory, must go through this training. One goal in the designing of the environment from the student point of view is to complete the orientation and receive a 3D-printing license, which entitles the owner to independent printing without supervision. This would act as a quality certificate in using the equipment.

9.4 Integration of engineering design and 3D CAD to AM

The efficient combination of engineering design, 3D CAD and AM requires an operational model, which collects these together. Usually a visual process model speaks for itself and it makes the presentation of the process easier. Main purpose of the model is to present the place of 3D printing and active learning in AM in the generic product design process. This way 3D printing is a part of the design process and not a separate function. 3D printing can easily be used as a follow-up to 3D modeling with the printing event but to achieve more efficient outcome, the necessary background has to be incorporated. The generic product development process works always as the background for designing new products and parts. This part of the work presents the improved version of the PD process model, which combines also engineering design in general, 3D modeling and AM. Figure 56 presents the new improved model for AM product design.

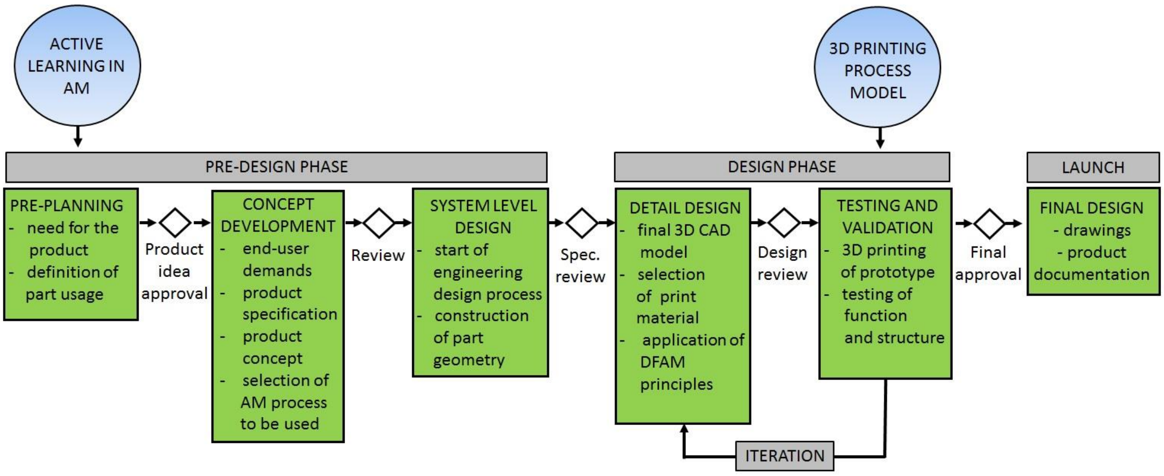

Figure 56. Improved process model for AM product design.

The model shows that the model for active learning in AM must be incorporated to the students work right from the start. This gives them the view to AM so that they understand the design process also from the printing point of view. The AM printing process model takes place in the testing stage in which the printed object or assembly is used to investigate the product specifications and function. If the result is not accepted, the changes can be made through iteration.

9.5 3D printing – assignment possibilities

Efficient way to learn 3D printing is to follow given assignment, which presents all the necessary aspects for learning. Purpose for pre-planned assignments is to ensure the level of expertise of the student for continuing to independent work. The assignments can be implemented in two different ways but both of them lead to the same result.

- Part of a course (e.g. Course in 3D printing).
- Independent learning package with teacher supervision: assignments are structured so that by going thru the assignment, the student is able to perform 3D printing independently.

The best result is that the student is able to design and print the part independently without supervision. It is also important that the student grow to understand and handle also issues such as:

- problem situations in printing
- evaluation of the print quality
- identify the need of post-processing of the printed part
- safety in 3D printing
- recognize the place for 3D printing in the product design process.

This section presents two different learning assignments; the first prepares the student for the printing process and DFAM basics and the second familiarizes the printing process itself through printing task. These assignments are tested with a student group, which gives feed-back from the assignments. The feedback will be used to improve the assignments and create finalized AM design process chart.

9.6 Learning assignment no. 1 – introduction to AM

Purpose of the first learning assignment is to familiarize the student to AM basics. This will cover the following topics:

- introduction to AM and basic principles
- general additive manufacturing process
- different AM technologies (main focus will be on FDM): (VAT photopolymerization, powder bed fusion, extrusion based systems, material jetting, binder jetting, direct energy deposition, sheet lamination)
- post-processing of the print
- DFAM (Design for Additive Manufacturing)
- AM product design process and printing process chart (including engineering design process revision).

The assignment will contain introduction lectures if it is arranged within a course. If not, the assignment will precede independent learning through flipped learning method. In this case, the necessary source of information will be pointed out to the student and it can be con-structed to a learning platform such as Moodle or similar. The flipped method is based on the independent learning of a student and the knowledge is phased for efficient learning result.

The testing of the assignments are arranged within an existing 3D CAD (3 ECTS) course in this thesis. Amongst the normal course topics, it contains introduction lectures to the AM subject. For future purposes, the assignments are integrated to 5 ECTS 3D printing course, which will concentrate completely to 3D printing.

This assignment will give the student sufficient background information about AM and especially FDM technology. Evaluation of the task will function as a quality assurance. The grading is based on ACCEPTED or FAIL and the student will receive a written feedback about the task. The purpose of the feedback is to point out the strengths and weaknesses in the knowledge and also give information what to improve. If the student passes the assignment, he/she is able to continue to the second assignment. This will function as a "driver's licence" to use the printers. If the student does not pass the assignment, he/she will be given feedback what to do in order to pass. The structure of the assignment is presented in figure 57 and the assignment instructions can be found from ANNEX I.

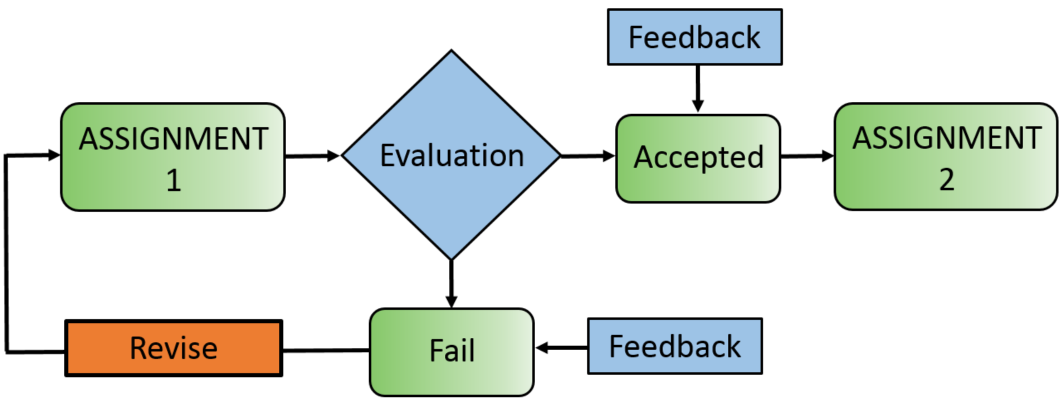

Figure 57. Learning assignment 1.

9.6.1 Student tests for learning assignment no. 1 and feedback

The target group was kept relatively small to achieve best possible results for the first experiment. Size of the group was six students; all of them were from the mechanical engineering degree. The assignments were given through Moodle platform and the feedback was collected after the first assignment by using the Moodle feedback tool. The questions were based on numerical and written questionnaire. The numerical question used scale from 0 to 5, where 0 = worst, 5 = best grade. The feedback was collected through the following questions:

1. Understandability of the assignment (scale 0-5).
2. Assignment gave good source information for 3D-printing (scale 0 – 5).
3. Opinion about the assignment (clarity, difficulty etc.) (written).
4. Did the assignment and source material give you sufficient expertise to perform the assignment? (written).
5. What is your opinion about the learning portfolio (does it help in learning, organizing the knowledge, what kind of harm it causes etc.) (written).
6. How do you feel about the process in the assignment? (start info, independents work, evaluation etc.) (written).
7. What development ideas you have for the assignment? (written).

The results from the numerical questions were presented as follows and they are presented in tables 4 and 5:

1. Understandability of the assignment.
2. Assignment was good source of information.

Table 4. Assignment 1 understandability.

Grade	Amount	Percentage
0 (Bad)	-	0,00 %
1	-	0,00 %
2	-	0,00 %
3	-	0,00 %
4	5	83,33 %
5 (Very good)	1	16,67 %
Average	**4,17**	

Table 5. Assignment 1 source of information.

Grade	Amount	Percentage
0 (Bad)	-	0,00 %
1	-	0,00 %
2	-	0,00 %
3	-	0,00 %
4	3	50,00 %
5 (Very good)	3	50,00 %
Average	**4,5**	

Results from the written parts were collected with the questionnaire. They are presented as follows:

3. Opinion about the assignment:

- topics and instructions were clear and timetable was well informed
- usage of English gave some challenges
- the goals were presented clearly
- writing was challenging.

4. Sufficient know-how:

- assignment gave sufficient know-how for learning purposes
- lot of information was presented and not everything was adopted
- better introduction to sources is required
- source material (3D Hubs) was very extensive and needed information was easy to find.

5. Opinion about the learning portfolio:

- writing the portfolio took big portion from the timetable
- learned knowledge was easier to adopt through the portfolio
- learning through writing is easier
- learned issues were easier to adopt through writing
- lack of experience in writing learning portfolio presented challenges.

6. Process of the assignment:

- source information for the assignment was good and well given
- the evaluation and feedback process is good; if there is possibility to drop out from the process, they will help you get back into track
- good ensemble for learning 3D printing basics
- works well if you have a slight knowledge of the basics
- for person, who doesn’t know nothing about the subject, it may present to be challenging.

7. Development ideas:

- comprehensive introduction lecture to the beginning; helps in acquiring information for the assignment
- portfolio could be even a bit more extensive; 1-2 pages per subject
- tight schedule works well for the assignment; it should be at least 2 weeks
- self-repeating parts could be removed and/or e.g. connected into one question.

9.7 Learning assignment no. 2 – 3D printing

Purpose of the second assignment is to familiarize the student to FDM technology through design work and practical laboratory work. This will cover the following topics:

- Drafting idea for the part: topic from real life need.
- Designing and modeling the part; creating necessary files for slicing and printing.
- Following orientation lecture about Minifactory printers; introduction of FDM technology. Presentation of Minifactory Kampus-videos.
- Working and safety in the AM environment.
- Printer setup and printing.
- Post-processing of the part (e.g. removal of supports, printer clean-up).
- Inspection of the part; measurements and forms compared to the original design.
- Result evaluation; planning what must be changed in the design and implement the changes. Presentation of results to teacher and feedback discussions.
- Re-designing and re-printing the part.
- Final reviewing of the part and conclusions; feedback discussions with teacher.

This assignment contains mainly practical work and many of the stages will be discussed with the teacher. The student will write report about the process and results with necessary conclusions. The teacher works as support personnel / supervisor in the process and the student has the freedom to plan his/her own progress. The structure of the assignment is presented in figure 58 and the assignment instructions can be found from ANNEX II along with the grounds for evaluation.

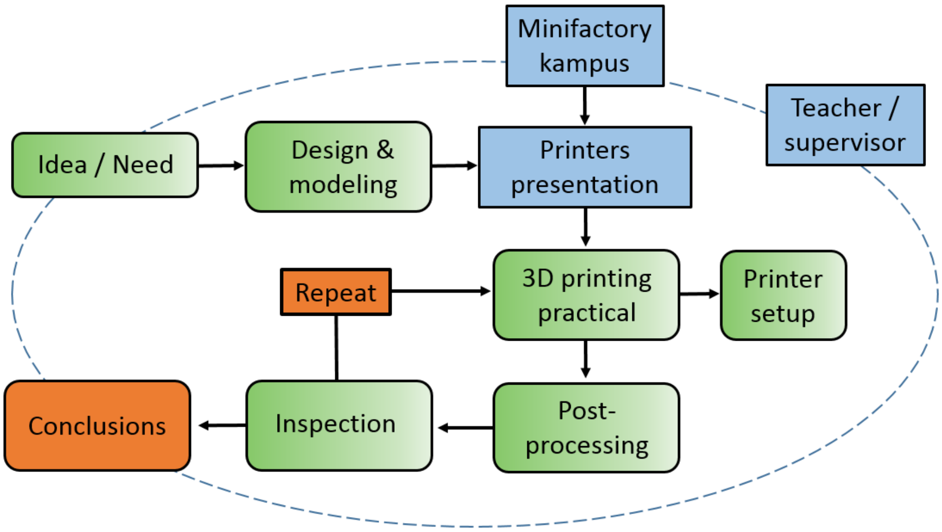

Figure 58. Learning assignment 2.

9.7.1 Student tests for learning assignment no. 2 and feedback

The feedback from the second assignment was collected in the end stage of the assignment. The students progressed with different phase so while some had performed the whole process, some were doing the prints and conclusions. The reservation of the printing time was sometimes an obstacle since all the students were using the Innovator printers. This caused delays in the printing tests but all of the students were able to perform the printing.

The feedback was collected through the following questions, which differ some from the questions from the first assignment as follows:

1. understandability of the assignment (scale 0-5)
2. assignment gave possibility to learn 3D-printing in practice (scale 0 – 5)
3. opinion about the assignment (clarity, difficulty etc.) (written)
4. did the assignment and source material give you sufficient expertise to perform the assignment? (written)
5. what is your opinion about the phases of the assignment (did the phases help / hinder learning etc.) (written)
6. how do you feel about the process in the assignment? (part of the independent work, teacher support, performing the printing process etc.) (written)
7. what development ideas you have for the assignment? (written).

The results from the numerical questions were as follows and they are presented in tables 6 and 7:

1. Understandability of the assignment.
2. Assignment gave good possibility to learn 3D-printing.

Table 6. Assignment 2 understandability.

Grade	Amount	Percentage
0 (Bad)	-	0,00 %
1	-	0,00 %
2	-	0,00 %
3	-	0,00 %
4	4	80,00 %
5 (Very good)	1	20,00 %
Average	**4,2**	

Table 7. Assignment 2 enables learning.

Grade	Amount	Percentage
0 (Bad)	-	0,00 %
1	-	0,00 %
2	-	0,00 %
3	-	0,00 %
4	-	0,00 %
5 (Very good)	5	100,00 %
Average	**5**	

Results from the written parts were collected with the questionnaire. They are presented as follows:

3. Opinion about the assignment:

- instructions were very clear, an evaluation phase to each stage would we nice; just to think why e.g. a fault happened
- the expected results were described well, the length of the report was not defined, which gave freedom and the possibility to concentrate to subjects that are important to yourself
- when the goal was known, working with the assignment was fluent.

4. Did the assignment and source material give you sufficient expertise to perform the assignment?:

- yes, 3D Hubs and Minifactory Kampus offered solutions to most of the problems
- the sources given in the assignment gave lots of useful information, using the printers was done mainly independently and sometimes also the more experienced student helped if there was problems
- necessary material to perform the assignment was available.

5. What is your opinion about the phases of the assignment:

- the phasing gave clear view how the assignment proceeds
- the assignment was functional, there were no problems
- the phasing was good even though the timetable was tight, the clear division of the phases helped the progression of own work and learning new things
- the progression of the assignment was clear, it evolved also freely so that the phasing was only suggestive.

6. How do you feel about the process in the assignment?:

- the process worked well, the independent work suits well for a person who work according to the instructions
- good wholeness
- there was lot of independent work but teacher helped always when necessary, interesting subject and the freedom of design work gave lots of motivation to work independently outside the lectures
- the assignment was centered around independent work and teacher gave support always when necessary
- process worked well but the printing time reservation must be organized better, working solution also for using the printing room so that you do not have to use time for asking entrance from the staff and/or asking the leys to the rooms.

7. What development ideas you have for the assignment?:

- more versatile introduction to the printers and maintenance would be good
- installing the slicing software to all the computers of the classroom
- more consideration of the root-fault to the problems in the assignment would be good and also thinking the problems even before printing
- it is ok like this, no need for development.

10 CONCLUSIONS

Purpose and motive for doing this thesis was to design and implement functional learning environment for LUAS unit of technology in Kemi, Finland. LUAS acquired six FDM printers in fall 2016 and the goal was to introduce the technology to mechanical engineering students through the environment. The students could study and learn product design, engineering design and 3D printing from theoretical and practical point of view in the environment. 3D printing presents a way to explore practical learning from completely new perspective especially through DFAM principles. The thesis was connected to an ongoing 3D CAD course.

Methods used in the thesis were divided into theoretical and practical section. The theoretical section, which consisted of literature review, studied the basics of AM such as different technologies but the focus was kept in FDM technology. Reason for this was the acquired printers and also the nature of FDM technology; the introduction of 3D printing with FDM is relatively easier compared to other AM technologies. The theoretical section gave the necessary basic knowledge also from the creation of learning environment through CDIO principles and state-of-the-art review from existing printing environments in Finland and rest of the world. The practical section handled the creation and testing of the new learning environment. The environment divides into learning the basics of 3D printing and to practical work with the existing 3D printers. As a result, different models and processes were created to be used in the environment.

The practical section presented that the concept of learning environment is usually used when describing a place in which the students use equipment while learning. This concept can also be viewed more broadly especially through learning processes, which are based on active learning. Active learning model recognizes components for active learning in the environment. This is used to show the necessary factors of learning to the students. By recognizing these factors, learning will become easier since they offer a starting point for the learning process itself. The nature of engineering is usually very systematic even though it is based on creativity. By dividing learning into different stages, approaching the learning process becomes easier. Simplified 3D printing process model identifies all the stages for the actual printing work. This helps the students to function with the printers since the model was tailored for the printers and for the used slicing software. AM design process model combines generic product design process model with engineering design, 3D printing and especially the DFAM principle. This is used in designing products, which will be printed for different purposes such as prototypes or usable objects. These models are used in two different learning assignments, which were created for actual learning of 3D printing.

The first learning assignment introduces the technology and basics of DFAM to the students. Purpose of this is to give sufficient knowledge to the students for performing practical printing. The second assignment introduces the design work for AM in which the students have to design and print usable object for themselves. This clearly increases the motivation in doing the assignment. Learning assignments give the necessary theoretical and practical background for the student to evolve into an independent expert who is able to use additive manufacturing in the product design process. The learning assignments were tested within the 3D CAD course with a small students group and feedback was collected for further development of the environment.

Developing the 3D printing environment is essential to keep up with the common technological development. Development must be viewed from the technological and pedagogic point of view. The environment can provide also other means to learn AM and also increase the knowledge within partner and cooperation groups.

11 FURTHER STUDIES

When learning is connected to technology, development must always be continuous. The creation of any kind of learning environment requires lots of effort but if the development is left undone after the creation, learning itself will remain only to one level. The following section contains different areas in which the learning environment created in this thesis will and must be developed.

11.1 Learning assignments

The two learning assignments and the feedback from them showed that they have to be developed further even though the feedback was almost purely positive. The involved students presented good ideas, which will develop the environment especially from the student point of view. The positive remarks in the feedback will be used as a confirmation of the functionality of the assignments. The main issues that will be developed are:

- more guidance in writing learning portfolio
- slightly broader portfolio (max. two pages per topic)
- more efficient introduction lecture before the assignment
- reflection to each stage of the second assignment; e.g. why certain fault happens?
- functional printing time reservation system must be created
- independent access to the printers (now behind locked doors)
- more reflection of the fault; finding the root-faults
- more introduction in using the printers and maintenance
- installation of the slicing software to the computers in the classrooms; no need for own laptops.

11.2 Technology and environment

The development of 3D printing technology is fast and therefore it is important to keep the equipment in the environment as modern as possible. The efficient development of the environment requires other technologies even though FDM gives good starting point for learning 3D printing basics. The following presents some suggestions with reasoning to acquire certain technologies:

- SLA/DLP: desktop size, new perspectives to DFAM, high resolution and surface quality, reasonable low price for equipment – possibility to acquire several printers, different usable resins, higher printing costs compared to FDM.
- PolyJet: good resolution and surface quality, higher price for equipment, easily removable support material, accurate geometry and dimensioning, multiple colors and/or materials into a single part.
- Material jetting: different materials than usual plastic (e.g. wax), good accuracy and surface finish, fragile parts – only for prototyping, higher price for equipment .
- FDM (different manufacturer): possibility to compare the features of different FDM equipment, possibility to perform more simultaneous printing (at the moment the number of the bigger FDM equipment is limiting the student printing)
- Handheld scanners; possibility to have free scans of different targets, possibility to re-engineer.

As with the technology, functional learning environment requires good facilities to implement guided and independent learning. Currently the printers are situated in two different rooms but the plan is to acquire one unite space for the printers. The requirements of the space were presented in chapter 9.2., which will be implemented in the near future at LUAS unit of technology.

11.3 Research

Additive manufacturing offers large variety of information to be explored and during the implementation of the learning environment and the assignment it was noticed that the development also requires different research approaches concerning the equipment and material, few to mention. The following presents ideas for extending the knowledge base. Some of them are already in implementation (e.g. two BSc theses at the moment):

- Bachelor and master theses: students have been very interested in developing the environment and theses are natural way to let the students to participate in the development. Plastic material science is not an expertise of our university and therefore it would be reasonable to use cooperation of partner universities and investigate the plastic materials further and at the same time create the expertise to own university. This would also include the research with the recycling of printed part and creating our own filament.

- Flipped learning possibility: the environment and the assignments enable the creation of flipped learning methods (which were already tested with the assignments). This would fortify the existing learning assignments and create the possibility for completely new independent learning package.

11.4 Prototyping centre concept

One way to look the learning environment is to consider it as a prototyping centre or concentration. The environment would function as a place, where the students could work within AM topics at the same time learning and even performing necessary work training for the degree. It would combine the aspects of engineering design work, AM and scanning if necessary. The centre would offer prototyping services for cooperation partners and would function as a knowledge provider for those who seek information about AM (in theory and in practice). The concept of the centre is presented in figure 59.

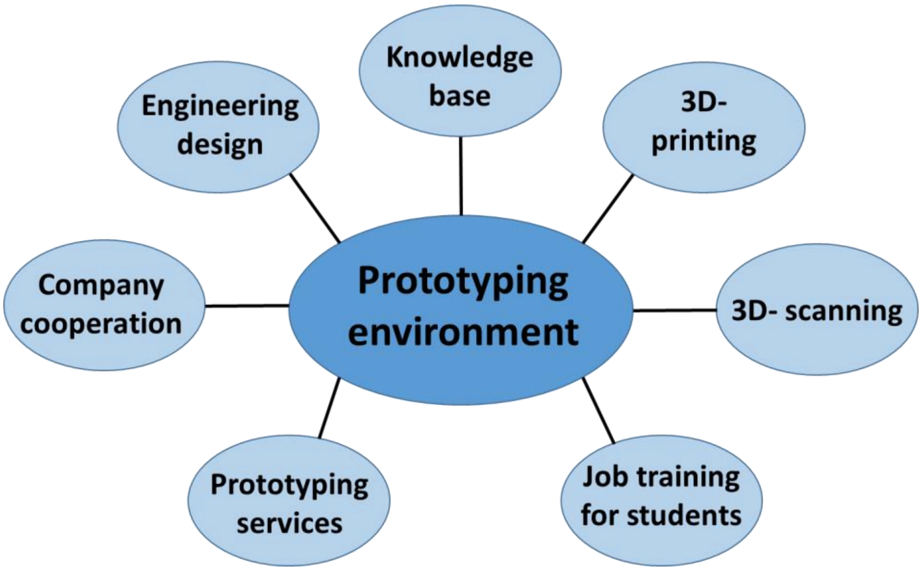

Figure 59. Prototyping environment concept.

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LAPIN AMK
Lapland University of Applied Sciences

The Unit of Technology

3D Printing

LEARNING ASSIGNMENT 1 – ADDITIVE MANUFACTURING BASICS

The purpose of the assignment is to familiarize to additive manufacturing. The main topics covered are:

- Introduction to AM and basic principles
- General additive manufacturing process
- Different AM technologies (VAT photopolymerization, powder bed fusion, extrusion-based systems, material jetting, binder jetting, direct energy deposition, sheet lamination). Focused on FDM-technology.
- Post-processing of the print
- DFAM (Design for Additive Manufacturing)
- AM product design process and printing process chart

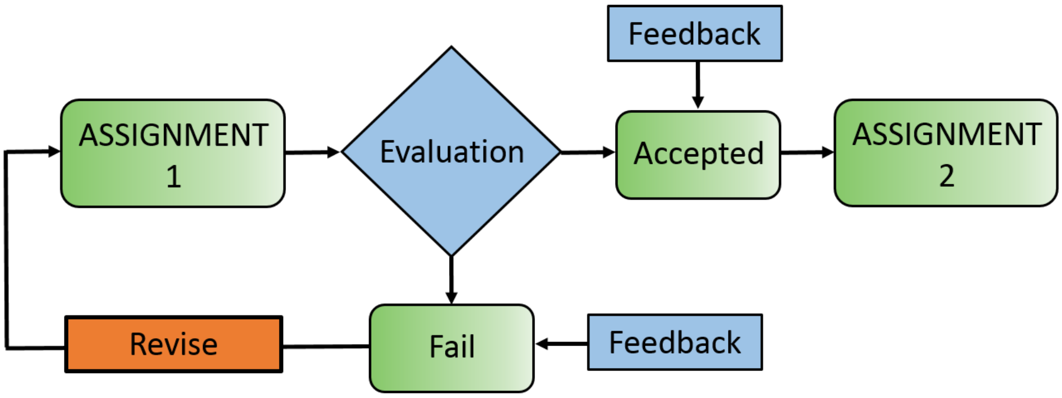
Source material can be found from the course Moodle site. Listen to the orientation lecture and familiarize the given material from Moodle.

After this:

1. Write an learning portfolio about the topics, which include:
    - reflections from all the topics; what were the main issues you learned, what were the important facts in your opinion etc.
    - find an example from each topic and include it to the portfolio
    - explain the example shortly and connect it to the current topic
    - maximum amount of pages: 8 (including the cover and table of contents, 1 page per topic)
2. Return the portfolio to Moodle according to the deadline.

3. Prepare for oral hearing concerning the portfolio: discussions with the teacher about the contents of the portfolio. The hearing event will act as feedback session for the results and the grading will be presented and justified in this event.

The assignment process will be arranged to the following figure:



Deadline for the portfolio:
Enter the return date here

Oral hearing:
Reserve time from the teacher for the hearing. Length of the hearing is maximum of 15 minutes.

Evaluation:
Accepted (ACCEPTED / FAIL)

In case of **YES**, you are permitted to continue to ASSIGNMENT 2.

In case of **NO**, the teacher will give feedback and the portfolio must be improved. The improved portfolio will be returned as revised to Moodle and additional hearing will be held. The revised portfolio has to be returned within **1 week** from the original hearing. Timetable of the additional hearing will be discussed with the teacher.

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3D Printing

LEARNING ASSIGNMENT 2 – DESIGN AND PRINTING

Purpose of the assignment is to familiarize to the designing of a 3D printed part from the engineering design point of view and perform 3D printing and post-processing.

Design a printable part, which incorporates the DFAM (Design for additive manufacturing) principles and basics of engineering design. Idea for the part must come from your own need (e.g. for some household application or spare part, car part etc.) and it has to have a function. Get approval for the topic from teacher. When design work is ready, reserve time for printing from the reservation list that can be found from Moodle.

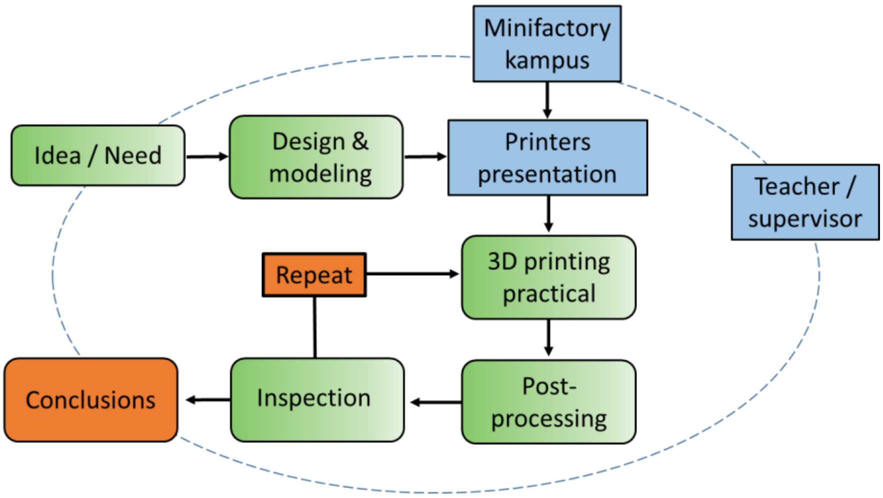
Write a report in which you present the progress of the stages and the reflection of the results. Use photos from the manufacturing process and results. The report will be returned to Moodle.

Stages:

1. Draft idea for the part; present the idea to teacher and get approval
2. Design and model the part; create necessary files for slicing and printing
3. Follow orientation lecture about Minifactory printers and the AM environment; introduction of FDM technology. Presentation of Minifactory Kampus-videos.
4. Working and safety in the AM environment
5. Reserve time for printing from Moodle
6. Printer setup and printing; view the Minifactory Kampus-videos
7. Post-processing of the part (removal of supports, printer clean-up)
8. Inspection of the part; measurements and forms compared to the original design
9. Result evaluation: Plan what must be changed in the design and implement the changes. Present the printed part to teacher for discussions.
10. Re-design and print again

11. Final review of the part and conclusions. Present the final part for teacher for discussions.

The assignment process will be arranged to the following figure:



Deadline for the report:

Enter the return date here

Evaluation:

Scale: 1 - 5

1 = Student has satisfactory skills and understanding about the topics. Student is able to design and print with guidance. Student is not able not evaluate the result by his/her own. 3 = Student has good skills and is able to perform independently with minor need for guidance. Student is able to evaluate own result with good results.

5 = Student possesses excellent skills in designing and printing and is able to function fully independent. Student is able also to advise other student and possesses excellent competence in evaluating own work and results.

Feedback:

Oral feedback will be given when presenting the part to teacher.

Written feedback about the report will be given through Moodle together with the grade.