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Survey on the Possibilities of Utilizing Metal Additive Manufacturing at an Industrial Company

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Abstract

The assignment for the bachelors' thesis was given by Valmet Jyväskylä. The topic was to survey the possibility of utilizing metal additive manufacturing at the company. The goal was to find potential applications, evaluate the manufacturing costs and define the factors that need to be considered when designing metal additive manufacturing.

Surveying the applications started with studying the theoretical background. Based on this a presentation of the possibilities and the limitations of metal Additive Manufacturing (AM) was presented to several groups to give Valmet personnel a basic understanding of metal AM. A questionnaire was used to collect ideas. Additional ideas were produced through observations and interviews. They were grouped, and the suitability of the candidates was evaluated using a weighted criteria evaluation chart. Two potential ideas were selected for an experimental study to prove the benefits of AM. Requirement lists, simulation software and professionals in the industry were used to support the design.

The results included a list of potential applications and a calculation tool, which were used in three different scenarios. Both experimental study parts benefitted from AM and the functionality improved without increasing the costs of the manufacturing to an unreasonable level. Based on the results, a proposal of the aspects to be further developed was made.

Based on the results, investing in a metal AM machine could not be justified even though there were many suitable applications. Metal additive manufacturing offered possibilities that traditional manufacturing methods were not able to and therefore the development work should be continued in co-operation with the service providers.

Keywords/tags (subjects)
3D printing, metal 3D printing, metal additive manufacturing, designing for additive manufacturing, evaluation tool, surveying ideas, manufacturing cost calculation

Miscellaneous (Confidential information)
Appendices 2, 3, 4, 5, 6, 7, 8, 9, 10 and 11 are confidential and they have been removed from the public thesis. Grounds for secrecy: Publicity law 621/1999 24§, 17, Business or professional secret. The period of secrecy is five years and it ends 22.5.2023.

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Metallin ainetta lisäävien menetelmien hyödynnettävyyden kartoitus teollisuusyrityksessä

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Tiivistelmä

Opinnäytetyön toimeksianto tuli Valmetin Jyväskylän toimipisteestä. Aiheena oli kartoittaa metallin Ainetta lisäävien Menetelmien hyödynnettävyys (AM) Rautpohjan toiminnoissa. Tavoitteena oli löytää sopivia käyttökohteita, arvioida valmistuskustannuksia ja löytää suunnitteluun vaikuttavat tekijät suunniteltaessa ainetta lisääville menetelmille.

Käyttökohteiden kartoitus aloitettiin perehtymällä teoriataustaan. Sen pohjalta valmisteltiin esitys metallin AM mahdollisuuksista ja rajoitteista, joka pidettiin useille ryhmille, jotta työntekijät osasivat arvioida tuotteiden sopivuutta omatoimisesti. Ideoiden kerääminen toteutettiin pääasiassa sähköisellä kyselylomakkeella, mutta lisää ideoita tuotettiin havainnoimalla ja haastattelemalla henkilöstöä. Ideat ryhmiteltiin ja soveltuvuuden arviointi toteutettiin arvotaulukolla. Potentiaalisimmista ideoista valittiin kaksi tapaustutkimukseen, jolla pyrittiin osoittamaan AM:n hyötyjä. Suunnittelun tukena käytettiin vaatimuslistaa, simulointiohjelmia ja alan ammattilaisia.

Tuloksena syntyi lista sopivista käyttökohteista ja kustannuslaskelma valmistuskustannuksista kolmessa eri tapauksessa. Molempiin tapaustutkimuksen kohteisiin saatiin tuotettua lisäarvoa suunnittelemalla ne valmistettavaksi AM menetelmillä ilman, että kustannukset nousivat kohtuuttomiksi. Lopuksi tehtiin perusteltu ehdotus jatkotoimenpiteistä.

Työn perusteella ei voitu ehdottaa investointia metallitulostimeen, vaikka sopivia käyttökohteita löytyi runsaasti. Kuitenkin, metallin ainetta lisäävät menetelmät tarjoavat mahdollisuuksia, joita muut valmistusmenetelmät ei tarjoa ja siksi kehitystyötä tulisi jatkaa yhteistyössä alan toimijoiden kanssa.

Avainsanat (asiasanat)

Ainetta lisäävä valmistaminen, 3D tulostus, metallin 3D tulostaminen, suunnittelu ainetta lisääville menetelmille, arviointityökalu, ideoiden kartoitus, valmistuskustannuslaskenta

Muut tiedot (salassa pidettävät liitteet)

Opinnäytetyön liitteet 2, 3, 4, 5, 6, 7, 8, 9, 10 ja 11 ovat salassa pidettäviä ja piilotettu julkisesta versiosta. Salassapidon perusteena on Julkisuuslain 621/1999 24§, kohta 17, mukainen yrityksen liike- tai ammattisalaisuus. Salassapitoaika viisi (5) vuotta.

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1 Introduction

1.1 Subject

Additive manufacturing (AM) has recently become a reckoned method to produce parts alongside the traditional manufacturing methods among industrial operators. In spoken language, the term 3D printing is generally used. Originally additive manufacturing was used for rapid prototyping, RP, to create physical examples of the products that were designed. Obviously, the physical model is much more applicable for a designer in order to improve the design. The technology improved with big steps and AM materials and machines achieved the needed quality to be used in assemblies. This offered the possibility to produce objects with small enough tolerances so the products could be used to form the whole system and eventually evaluating the functionality of a system became possible. (Gibson 2010, 3-4.)

Nowadays quality of the AM process has reached the level to be suitable for end use applications in manufacturing industry. The development of the technology has been furious. It is presumable that in the next years the competition will increase and purchase prices of metal additive manufacturing machines will decrease to a more reasonable level because of many significant patents have expired during 2010s (Hornick & Bhushan 2016). Even though the perceptions diverge among the authorities the possibilities of AM technology must be surveyed now.

Additive manufacturing corresponds with many of the global megatrends. International consulting and engineering company Pöyry has studied the global megatrends in paper industry. 3D printing is listed as one of the technological trends and many related topics are pointed out under different categories. For example, competition on limited resources motivates companies to invest material saving technologies which is typical for AM. Less material is used more wisely during shorter manufacturing process and therefore it serves customers' responsible consumption trend. (World Paper Market up to 2030, 2014.) Still, Pöyry did not define more precisely the possible uses which offered more possible outcomes for this thesis.

1.2 Company

Valmet is a multinational company that employ over 12 000 employees globally. The activities are based on four business lines: paper, services, automation and pulp and energy. With over 220 years of history in industry and many fusions with other operators has spread Valmet all over the world. The services cover 33 countries, 120 service centers and 34 production units. EMEA (Europe, the Middle East and Africa) consist the most of employees and current customers. (Valmet general presentation 2017.) The turnover increased to 3,159 billion euros in 2017 from 2,926 billion euros in 2016 (Laine & Saarinen 2018). Valmet's mission is to convert renewable resources into sustainable results. The long-term vision is to become global champion in serving their customers. (Valmet general presentation 2017.)

1.3 Topic

As the competition in the paper machine manufacturing is extremely tight, Valmet must pursue new technologies to upkeep their technology superiority and find new ways to achieve price competitiveness. Valmet has seen the additive manufacturing as a potential field to study and get deeper understanding for a long time. Even though multiple studies and new applications pop up constantly, it is challenging to get to the latest information. Studies are made mainly by companies that do not want the information to leak to their competitors. Valmet has faced the same problem and the reasonable solution was to start the investigation by bachelor's thesis.

"A Survey of Possibilities to Utilize Metal Additive Manufacturing in an Industrial Company"

The topic offers widely different point of views to approach the matter. For example, sales person would be interested of how additive manufacturing could increase sales directly or indirectly. At the same time the manufacturing department would like to shorten the manufacturing time and amount of needed operations. Designers are restricted to follow the limitations of traditional manufacturing methods but additive manufacturing offers totally new degrees of freedom to improve the functionality.

The extensiveness of possibilities forced to limit the topic of this work. As stated before the thesis was a sort of kick off to implement the metal additive manufacturing to Valmet's processes so, the first facts the company needed was whether they have potential applications or not. Instead of concentrating how additive manufacturing change the production chain the work was limited to survey the most potential applications. After identifying the applications, the suitability needed to be proven. In this work, it was performed trough case study which was made to two concepts. Developing two products from start to state of end use was considered too demanding in this timeframe. Therefore, the primary goal was to find and show the possibilities of additive manufacturing methods, not solution-oriented designing. These boundary conditions formed the research questions and the main goal was to give straight answers to them:

- What are the most potential applications to use metal additive manufacturing in Valmet Rautpohja activities?
- What is the manufacturing cost in case of investment to the AM technology?
- What are the main factors to consider in designing for additive manufacturing?

1.4 Earlier studies

As stated earlier Valmet Rautpohja has no previous investigations regarding to metal additive manufacturing. Still some touches to metal additive manufacturing have been made since students have been working on a project and ended up to a design that would be optimal to produce by 3D printing. For example, Lauri Laakko and Ilkka Linnamäki developed a manifold that could be printed from acid resistant steel (Laakko & Linnamäki 2017). This particular work did not include the manufacturability and suitability evaluation for additive manufacturing but it forms the starting level for further study. Other existing studies approach the subject from more specified point of view and only few corresponding surveys were found during reference investigation phase. The list below shows similar thesis made by students:

- Jani Löfgren 2015 – 3D-tulostusmenetelmien käyttö auton osien valmistuksessa
- Jari Knaapi 2017 – 3D-tulostuksen liiketoimintamahdollisuudet
- Joel Jones 2016 - 3D-tulostustekniikan hyödyntäminen tuotekehityksessä ja valaisimien valmistuksessa

Below is a list of studies made by students from the similar subject or include the same main aspects:

- Juho-Petteri Storberg 2017 – Materiaalia lisäävän valmistuksen arvontuotto
- Emmi Välimäki 2017 – Modelling, simulation and validation of CMT process: an application for additive manufacturing
- Mikko Hovilehto 2016 – Characterization of design of a product for additive manufacturing
- Juho Raukola 2017 – Characteristics of metal additive manufacturing in four-stroke engine manufacturing process

1.5 Survey of current state

Valmet has already experience in additive manufacturing with plastics. The first fused deposit machine was purchased 2005. During the first 7 years, the machine was working over 7300 hours with ABS plastic. The machine has been supporting designing and development operations. Numerous prototypes, tools, miniature models and other parts have been printed successfully. In 2018 new plastic printer was purchased to replace the previous one with two printing head offering the possibility to use two different materials in the same build.

Not only plastic is printed at Valmet, but also metals. Valmets Sundsvall location uses metal AM to manufacture casting patterns for refiner segments. Many years different ways were studied to produce refiner segments more cost-efficiently but no solution was found. For example, machining time for the part presented in figure 1 below was over a week. During 2016 the metal additive manufacturing for commercial use started and nowadays they print the patters at roughly 50 % the cost if compared to traditional manufacturing. At the same time manufacturing speed increased and according to Traff this could be improved further. (Traff 2018.)

Figure 1. Manufacturing of refiner segments with traditional methods

According to metal AM industry pioneers Heikkinen (CEO at 3DStep) and Kananen (CEO at AMFinland) (2018) Finland is lagging behind of the rest world in additive manufacturing industry. There are much more service providers abroad if compared to Finland. Strong hype has abated and real applications are slowly being found. At the same time elsewhere, complete additive manufacturing factories are working and producing parts. Both Heikkinen and Kananen think that in the future additive manufacturing will take its place among traditional manufacturing methods and is often justified with lower environmental impact. Number of applications will increase and at the same time materials are developed further to be more suitable for AM demands. Both Heikkinen and Kananen has seen the development of customers' needs going more and more to end use production from prototyping. For example, Heikkinen from AMFinland states they manufacture more end products and product series than prototypes.

Using the FDM printers to prototype purposes has removed many prejudice regarding to AM technology in Valmet. Still most of personnel have too little fact knowledge about the technology which was observed during survey of a potential use. The lack of information reflects to prejudice and occurs as reluctance to change. This was the main research problem and the target was to increase the level of awareness.

1.6 General strategy

Selected strategy for this work follows the methodology for part selection presented by Lindemann, Jahnke, Reiher and Koch (2014) and is presented in figure 2 below. The method is divided into three different phases. During the information phase the AM technology is presented to stakeholders. This require the presenter to be familiar with the theoretical background of the technology, its possibilities and limitations. In this work it was done by research and preparing a general presentation of AM. After this the participants had the required knowledge to start screening the possible applications which were performed in this work with questionnaire and observation. The second phase (assessment) is a process to limit out most of the undesirable ideas and leave the most potential ones. Trade-off matrix and interviews were main tools for this phase. Thirdly, in the decision phase the final evaluation and selection were conducted together by thesis worker and thesis supervisors. After redesign process the prototyping and cost estimation formed the basis for evaluating process.

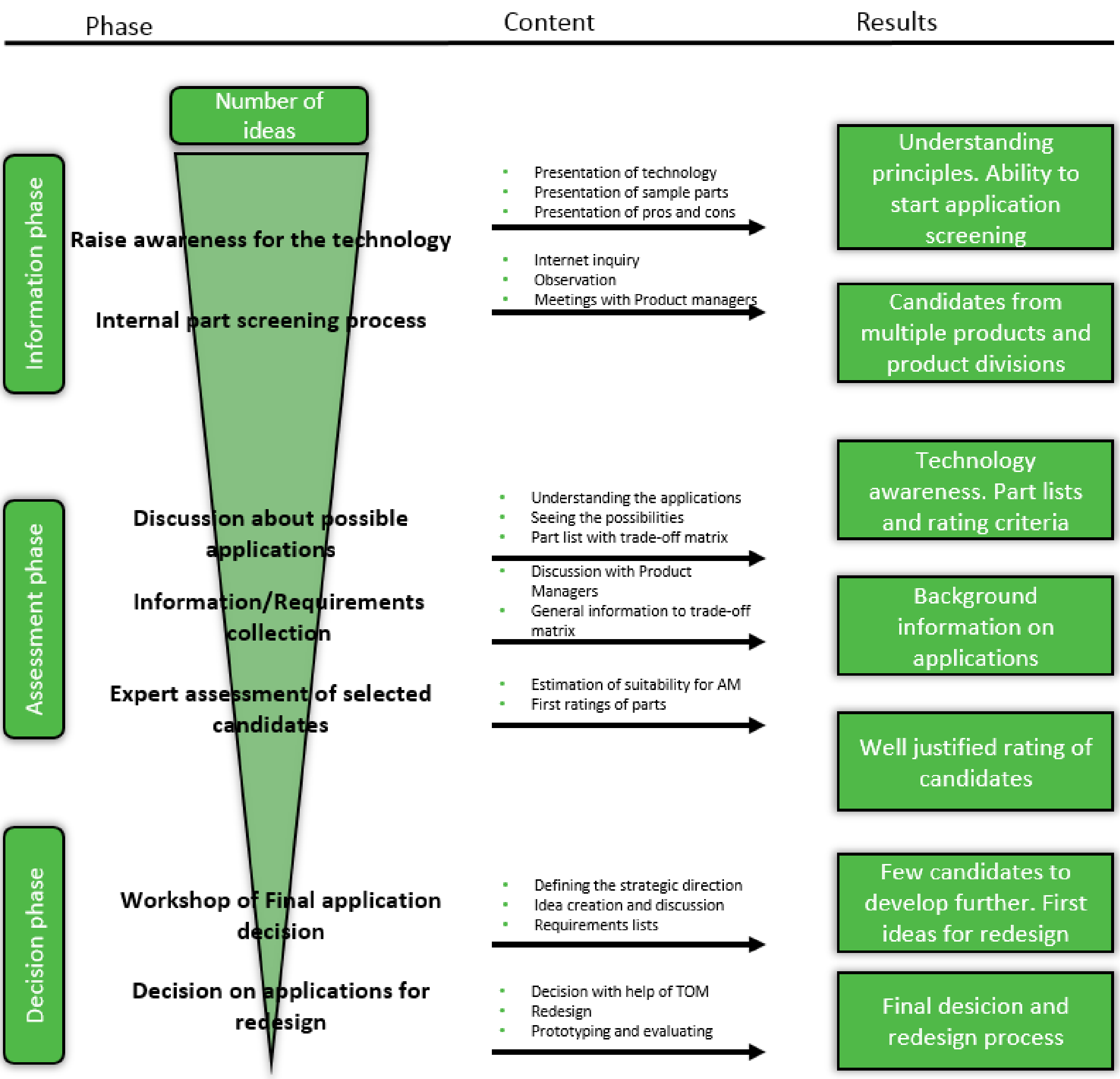

Figure 2. General strategy of the work (Lindemann & others 2014, 938 modified)

2 Research methods

This thesis was divided into three main parts: theoretical, survey and experimental part. In the theoretical part the basics of metal additive manufacturing, cost estimation and research methods to be used are presented. The theoretical part is based on scientific articles, textbooks, journals, educational materials and earlier studies made by students. The survey part proceeds according to action research which is combination of basics of qualitative and quantitative research methods.

2.1 Action research

Qualitative and quantitative research form the two general research approaches. The main difference is that quantitative research is based on numbers and their relations. Typically, qualitative research is used to help understand the phenomenon. The quantitative research is commonly used to specify more detailed matters of the phenomenon. Qualitative research investigates only few research units when quantitative research processes tens or hundreds of units. (Kananen 2010, 36-39.)

These two research approaches do not necessarily fit into every study and more tailored approach is required. In some cases, the study does not only aim to understand the phenomenon but also develop the operations to the next level. (Kananen 2009.) In this work the research approach is action research which is not purely a research approach like quantitative and qualitative approaches are, but a mixed methodology which include both or only qualitative research (Kananen 2017, 18).

The main difference between qualitative, quantitative research and action research is that the later aims to make a change. Not only to study the phenomenon but also produce development suggestions and evaluate the outcome. The main steps of action research are listed below. (Kananen 2012, 42-43, 52.)

1. Survey of current state
2. Analyzing the problem
3. Development of suggestions
4. Experimentation
5. Evaluating
6. Monitoring

According Kananen (2012, 63) deep understanding of the problem is the base of research and finding appropriate solutions. In this work the main problem was the lack of information regarding metal additive manufacturing so answering to research questions presented in chapter 1.3 Topic was the key to success. The main problem and related entities are illustrated in fishbone diagram in figure 3 below.

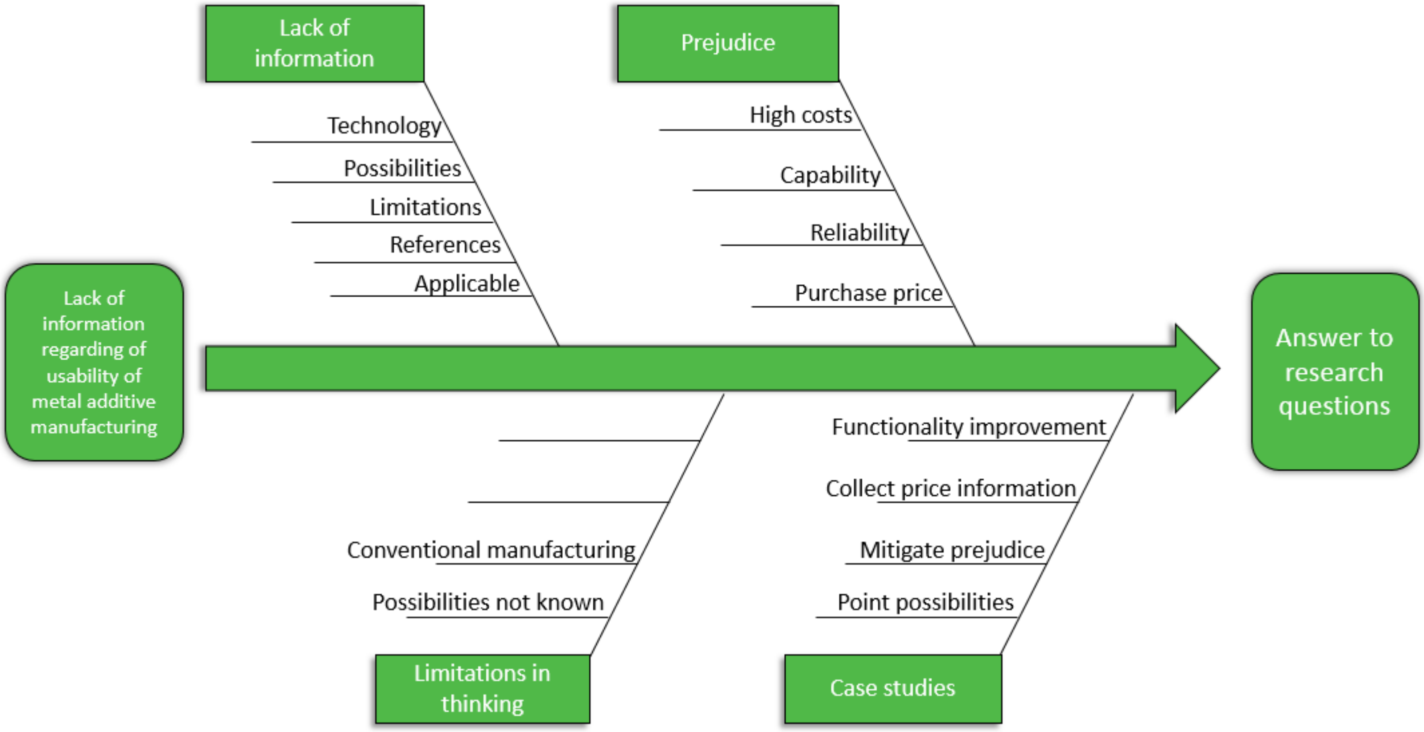

Figure 3. The main research problem and related entities

2.2 Gathering data

Scientific research requires numerical, written, spoken or other data to solve the problem. There are many methods to gather the data depending on the research approach. Documents, perception, interviewing are the three main types to gather data in qualitative research. The same methods are also applicable to action research. (Kananen 2017, 42-43.) In this work multiple data gathering methods were used depending on the phase of the study. Internet inquiry was used to survey the general background and previous experiences regarding metal AM and to gather potential ideas. Observation and interviewing were used to find more potential ideas and refine the existing ones.

2.3 Reliability factors

As any other research, also bachelor's thesis must be justified and reliable. New knowledge is produced using theoretical background as a base. The quality of the theoretical background is crucial in order to achieve reliable results. Two main terms are used to evaluate the quality of the study: reliability and validity. Reliability means the constancy of the results. Validity is the relationship between studied matters and the target matter. Both qualitative and quantitative research methods have their own factors to consider. (Kananen 2012, 161-163.)

2.3.1 Quantitative and qualitative reliability factors

Quality of quantitative research can be crystallized on reliability and validity. Reliability cannot be calculated and only way to evaluate it is repeat the study. With validity, the terms are the base of quantitative research to ensure correct understanding for every participant and stakeholder. The participants should present the target group if the study cannot be done to every individual. (Kananen 2015, 345-350.) In this work the quality was taken into account by avoiding complex industry specified terms and using internally settled terms in questionnaire. The target group was selected with help of supervisors to ensure sufficient and corresponding group.

According to Kananen (2015, 352) quality of qualitative research is not as straightforward as with quantitative research. The main terms are listed below with focused description. As the list shows most of the factors are evaluated after the study by other people using the documentation. Because of this the documentation was done during the whole work.

Main terms that define quality of qualitative research:

- Credibility - How well the results indicate with real situation according to member checking?
- Transferability - Qualitative research does not aim to generalize information
- Dependability - Is the research repeatable?
- Confirmability - The participants orientate and approve the result
- Saturation - The gathered data starts to repeat itself

2.3.2 Triangulation

Sometimes the research is complicated and wider approach is needed. This is typical in action study when only one research approach does not serve the goal with best possible way. Combining different methods from different research approaches will lead to more reliable result. This is called triangulation. The complexity is to know when to use a specific method because not always combining the methods end up to reliable result. (Kananen 2012, 178-179.)

In this work triangulation was applied to every main phase. For example, broadly different sources from industry experts to published studies were used to gather the theoretical background. The same way the application screening process was carried out using questionnaire, interviewing and observation. During the final design phase, the cost estimation was evaluated with help of service providers and cost calculations concerning multiple scenarios to produce reliable understanding of true manufacturing cost.

3 Additive manufacturing

SFS ISO/ASTM 52900:2015 define additive manufacturing as "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies". To accomplish this either CAD software or 3D scanning device is required. After this the model must be converted to stereolithography (STL) file format because nearly every AM machine accepts and CAD softwares output the STL file format. The file is transferred to AM machine and before building phase many general parameters are required. These might be for example layer thickness, print speed, location of the work piece and position. Then the next step is the building phase which is mainly automated process and only essential supplies needs to be taken care of. Building phase is followed by removal in which parts are removed from the machine. Some technologies require specific safety matters to pay attention. For instance: there is no moving parts and the temperature is decreased to permissible level. Now the operator has the physical part in his hands and depending on the requirements post-processing might be needed. (Gibson 2014.)

3.1 Examples of current use in industrial manufacturing

Siemens has managed to perform full-load test to 13-megawatt gas turbine with 3D printed turbine blades. Blades had to endure 1250 °C temperature, high centrifugal force because of revolution speed was up to 13 000 rpm and 11 tons carrying capacity. Blades were manufactured using SLM technology. (Siebert N.d.)

Renault truck engineers redesigned DTI 5 4- cylinder engine using the advantages of metal additive manufacturing. They managed to reduce the weight of the engine by 120 kg and number of parts by 200 fewer parts. The development was not only cosmetic but the motor with 3D printed rocker arms and camshaft bearing caps was bench-tested 600 hours. (Metal 3D Printing: Technology of the future for lighter and more compact engines 2017.)

Divergent 3D is taking car manufacturing to the next level by manufacturing complete supercars with 3D printing. Because of the new geometrical possibilities of joints and reducing the amount of needed parts the car chassis can be assembled in minutes instead of days. The company states 3D printed cars to be greener to manufacture and safer than traditional cars. With additive manufacturing the car industry does not need large mega factories to be cost efficient but more local highly tailored manufacturers are given the possibility. (Ohnsman 2017.)

3.2 Process categories

Additive manufacturing divides into multiple categories depending on the used technology. Each technology has its own possibilities and limitations regarding the reachable geometry, accuracy, materials and many other variables. Figure 4 below shows different technologies which can produce metal parts and a few machine suppliers for each technology. ISO/ASTM 52900:2015 uses the same separation for the main divisions. In metal AM the most machine builders rely on bowder bed technology fused by laser.

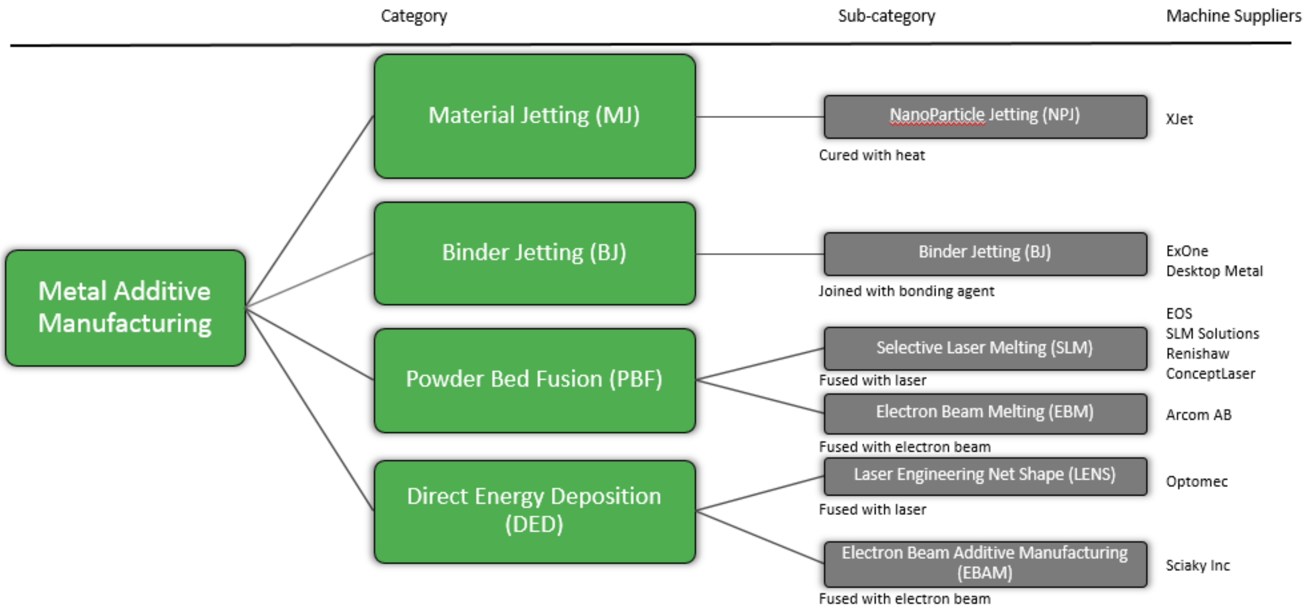

Figure 4. Metal additive manufacturing technologies and examples of machine suppliers (Redwood N.d. Modified)

3.2.1 Binder jetting

Binder Jetting (BJ) is additive manufacturing method that uses binder substance to join powder particles together. Main operating principle can be seen from figure 5. Binder is typically in a liquid form and the part is formed by dropping droplets of binder to desired areas. Then the building platform is lowered by height of one layer and a new thin powder layer is added. Each droplet is about 80 µm in diameter which has an effect to the typical layer height for metal parts to 50 µm. Normally the build volume is bigger than in PBF machines and can be up to 2200 x 1200 x 600 mm. It is commonly used to sand casting cores and molds. (Varotsis N.d.)

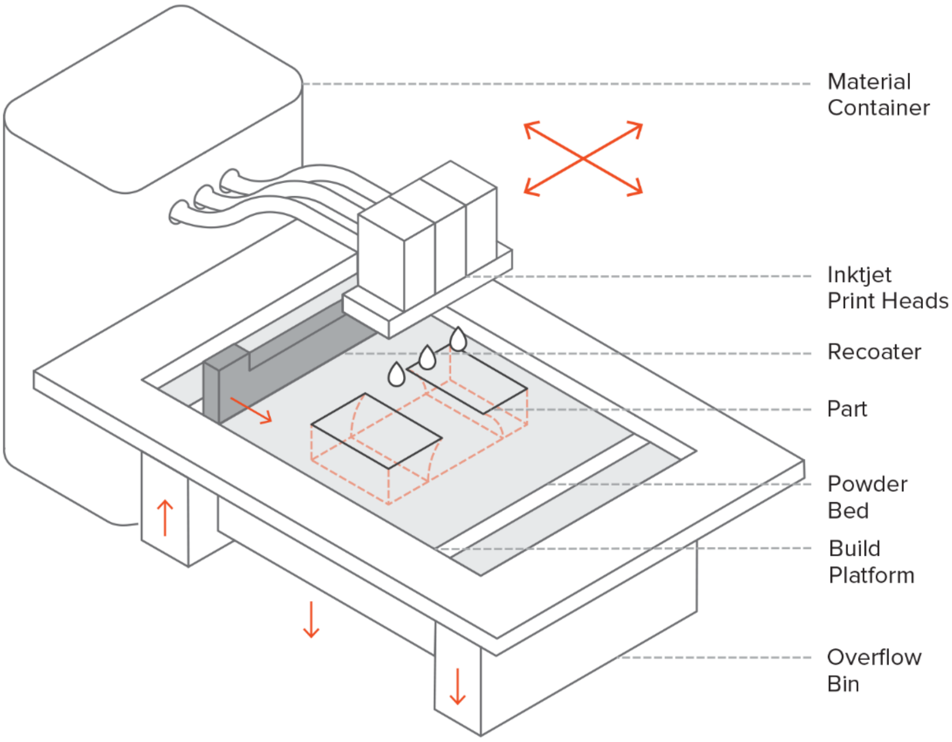

Figure 5. Schematic of a Binder Jetting 3D printer (Varotis N.d.)

If compared to PBF technologies the achievable mechanical properties are the main drawback because metal powder particles are not melted or sintered. On the other hand, this makes the binder jetting environmentally friendly because the energy is not used to change the state of the substance. (Varotsis N.d.)

3.2.2 Powder bed fusion

Powder Bed Fusion (PBF) uses a thermal source that causes sintering or melting of a metal powder. The thermal source is usually laser or electron beam. Powder bed fusion divides into subcategories depending of the thermal energy source and the joining method. Integrative factor is the metal powder which act as source material. (Redwood N.d.)

Direct Metal Laser Sintering (DMLS) was the first commercial method to produce metal parts. It uses high power laser that scan the powder layer until the particles are fused together. The new layers of powder are applied with recoater arm. As the process proceeds the build platform is moved down and powder supply platform is moved up (figure 6). (Castells 2016.) DMLS is useful in many applications because different materials can be used widely including alloy steel, stainless steel, tool steel and aluminum (Direct Metal Laser Sintering N.d.) Support structures needs to be created if the mass of the object exceeds the carrying capacity of the metal powder or if the part has bridge-like or hanging shapes.

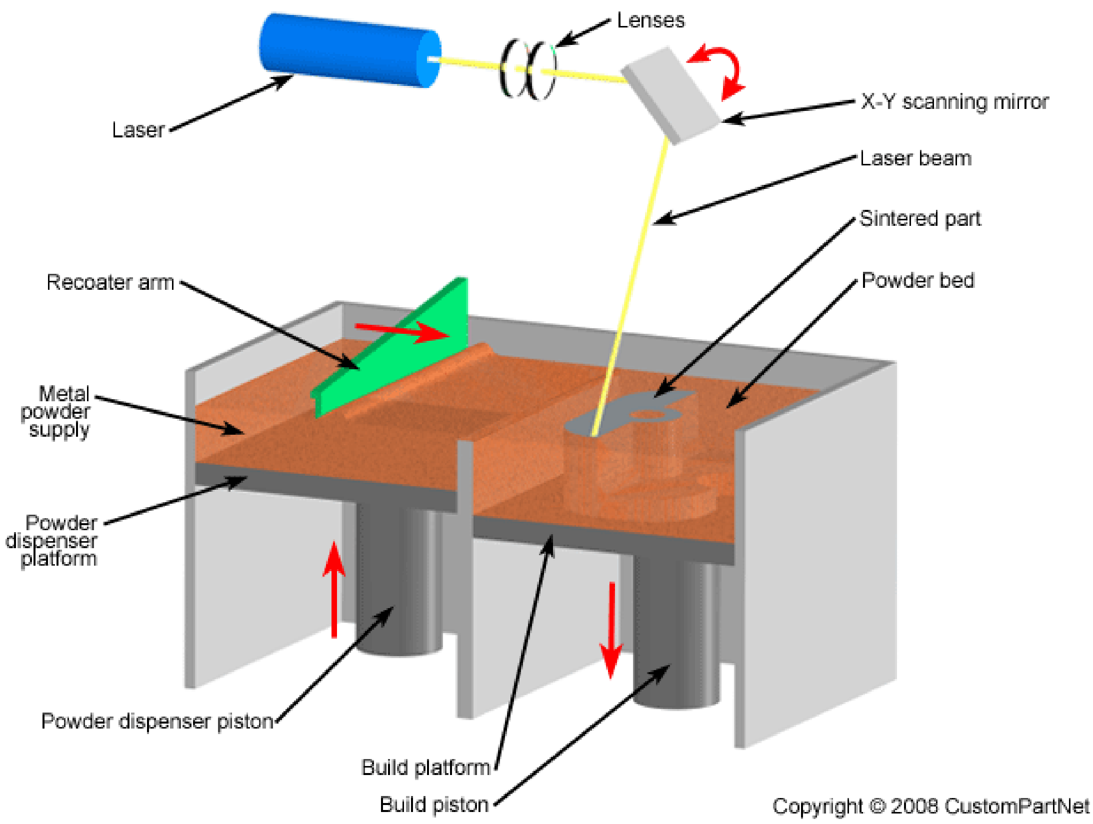

Figure 6. The main operating principle of Direct Metal Laser Sintering (Direct Metal Laser Sintering. N.d.)

3.2.3 Material Jetting (MJ)

MJ uses the inkjet method which deposit material droplets into a building platform (figure 7). At some cases, multiple types of material can be used for example to make the support material removal easier. Originally the technology was used to plastics and UV lights was used to cure the layers. Later XJET developed a machine that can print ceramics and metals. The method provides thinner layer heights and smaller details than other metal AM technologies. (High Level Processes: Material Jetting

2017.) XJET uses high temperatures to evaporate the unnecessary liquid from material droplets. Manufactured part need always sintering process. (Groundbreaking NanoParticle Jetting Technology. N.d.)

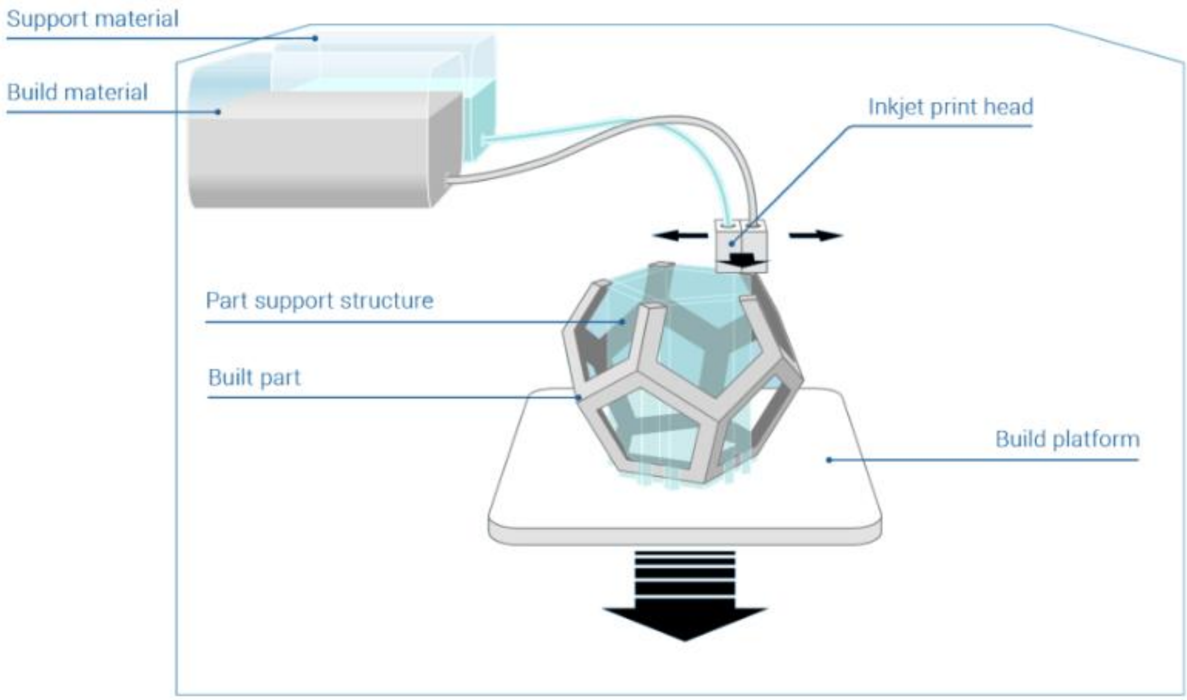

Figure 7. Basic principle of NanoParticle Jetting (High Level Processes: Material Jetting N.d.)

3.2.4 Direct energy depostition

Direct energy deposition is close to material extrusion known from FDM 3D printers. Typically a nozzle is mounted at the end of multi axis arm and material is directed on to desirable location where it solidifies as illustrated in figure 8 below. Material can be in a form of powder or wire. The heat source divides the technology to different methods. Laser Engineered Net Shape (LENS) uses focused laser and Electron Beam Additive Manufacture (EBAM) uses electron beam as a heat source. The multi axis movable nozzle is ideal for repairing broken parts or coating existing parts with different material than the base. (Redwood N.d.)

According to machine suppliers relatively big parts can be produced. For example, Sciaky Inc. promises 5791 mm wide, 1219 mm deep and 1219 mm high building area (The EBAM 300 System N.d.). The technology allows printing completely in horizontal direction without support structure that most of the AM methods require. The main drawback is poor surface roughness which is even worse than with PBF technologies because process is similar to welding.

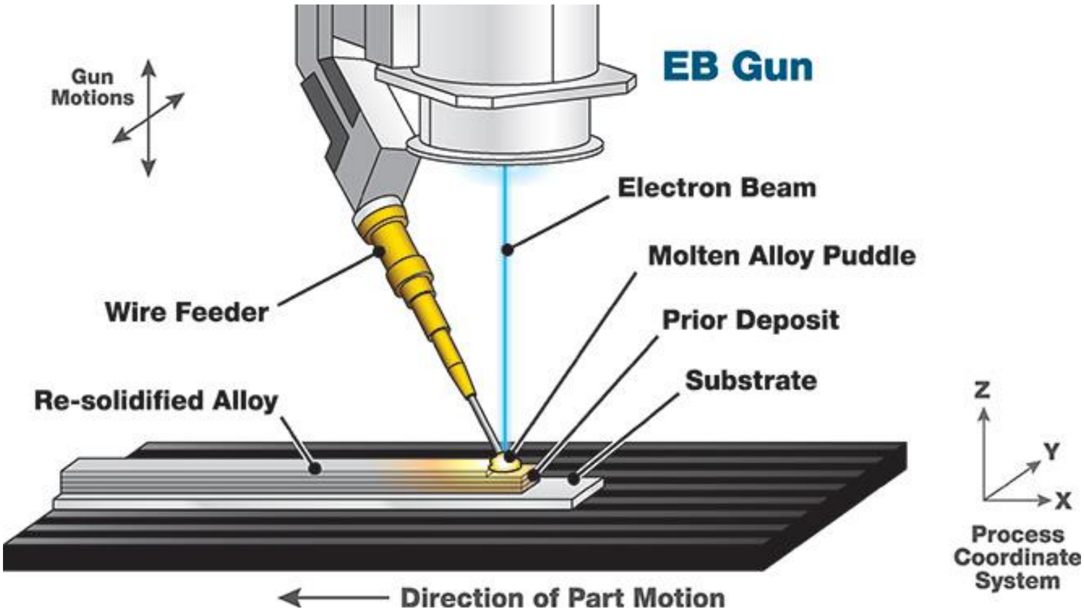

Figure 8. Directed energy deposition process based on wire feeder system and laser (Advantages of Wire AM vs. Powder AM. N.d.)

Tampere University of technology has a DED machine with 750 kg carrying capacity. It is based on ABB IRB4600-40/2.55 robot, ABB IRP A-750 workpiece positioner, Corelase 3 kW fiber laser and can handle pieces with 1000 mm diameter. They have experience for example of aluminum bronze. Laser scanning and measuring devices support the machine to recognize the workpiece. (Vihinen 2018.)

3.2.5 Bound metal deposition

A company called Desktop Metal developed the first metal AM machine which does not require specific facilities but can be installed into an office environment. They call the proprietary technology as “Bound Metal Deposition”. The metal bounds are extruded layer by layer on top of the building platform. The technology is similar to FDM desktop printers. Metal is not melted during the printing and the geometry keeps its shape because of adhesive included to the metal bounds. Printed parts are not ready to use after printing and need to be debinded with specific fluid. During the debinding the adhesive material is removed and the part changes to open-pore structure. After this the part is heated near to melting temperature. The particles fuse together and density increases. (Studio System, N.d.) The whole studio system including printer, debinder and furnace costs 120 000 €. This does not include training, installation and taxes. (Pricing 2017.)

The technology is promising and offers new possibilities for designers to use metal AM in prototyping. Unfortunately, information about a capability and dimension accuracy of the machines were not published so further conclusions were hard to make. It can be assumed that the industry is going to this direction and more affordable systems are coming into market during next few years.

3.3 Post-processing

Post-processing takes place when the AM-built part is ineligible for end use application as it stands. Not only the accuracy of the AM machine but the orientation, location and examined surface has an effect to the surface quality. (Post-processing of AM specimens 2017.) According to Nyrhilä, Kotila, Lind and Syvänen the surface quality of direct DMLS produced parts is one of the biggest problems because the method itself is aggressive. Some of the material stays in solid state and some particles melt so the surface quality cannot be very good without post processing. Therefore, from their opinion every surface that is critical for functioning should be finished. Vaajoki and Metsä-Kortelainen (2016, 9) state post-processing at least as important phase as building and the need for post-processing is defined by the requirement for the part.

Every AM manufactured part require post-processing at some stage. Usually post-processing is needed to clean the powder off and remove the support material from the part. The needed actions are depended on the used technology, amount of material to be removed, costs and needed surface quality. Because of high heat transfer internal stresses and porous structure are typical issues with metal additive manufacturing so correct heat treatment is used. Nowadays using correct post-processing methods, the most typical technical requirements can be achieved.

3.3.1 Powder removal

Powder removal is necessary treatment after every print if powder bed fusion technology is used. The powder consists of fine spherical particles. The particle size can vary but for example Renishaw provides powders that range between 15 µm and 45 µm (Metal powders for AM N.d). The finer the particle is the better is the quality of the print but on the other hand the powder is harder to spread evenly. Removal can be done using brush or vacuum machine. Notable is that the unused powder can be recycled. Powder removal is one of the phases that need labor work and machine operator is tied to production. Some manufacturers have integrated the powder removal/gathering system as part of the machines (e.g. EOS M400).

3.3.2 Support material removal

Support material is separated structure to support the build object which always occurs in printed metal parts because the object is printed on top of support structure to avoid attaching to the main building platform. The structure is designed to be in touch just enough to support the needed geometries but not to attach tightly to the printed object as illustrated in figure 9 below. Depending on the technology it can be dissolved chemically or must be removed physically. With metal the removal often requires tools and machines. With small parts the side cutters are usually enough for removal. With bigger parts wire cutting or band saw is needed to remove the main support structure from the building platform.

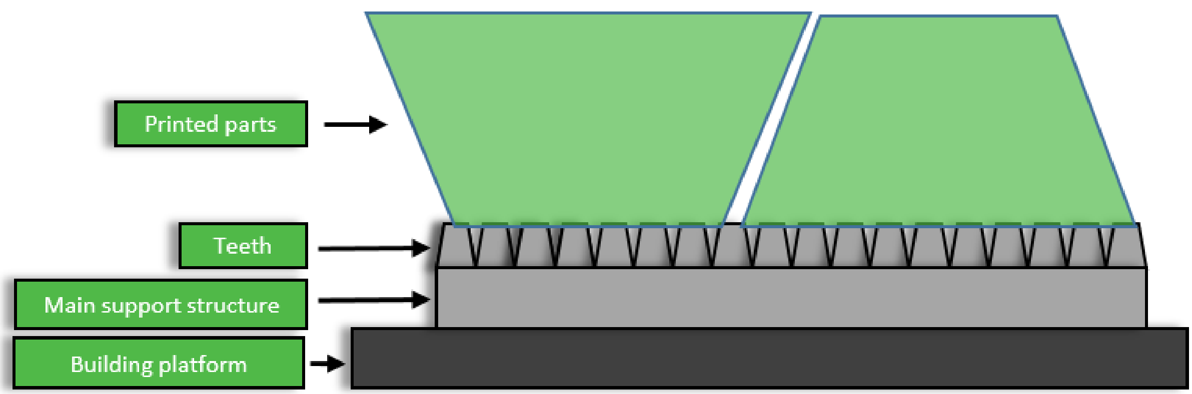

Figure 9. Support structure with teeth interface

At some cases the desired geometry requires support material to places that are hard to access which leads to difficult and long support material removal operations. This negate the benefits of AM. To solve this, researchers are investigating the possibility to dissolve support material chemically. Lefky, Wright, Nassar, Simpson and Hildreth (2017) studied this with stainless steel samples. As a conclusion, they were able to remove the support material with slight (100-200 µm in diameter) loss of material. This can be taken into account during the modelling process. (Lefky and others 2017, 3-10.) The study does not show the process impacts to material characteristics. In addition, the etching time was 32,5 hours which can be considered very high for rapid prototyping purposes. For this work the study shows the broad interest on metal AM and methods will improve in near future making the technology even more useful in industry.

3.3.3 Shot peening

Shot peening is similar to sand blasting but the round shots do not remove material from the part. Achievable surface properties depend from the used shot peening material as shown in figure 10 below. Peening material can be steel, ceramic or organic and the particle varies. During the build phase the material is melted together which generate internal stresses. Shot peening causes local impacts which makes the dislocations to move. This releases stresses which may improve the fatigue properties. Achievable surface quality is 3-10 µm. (Vaajoki 2017.)

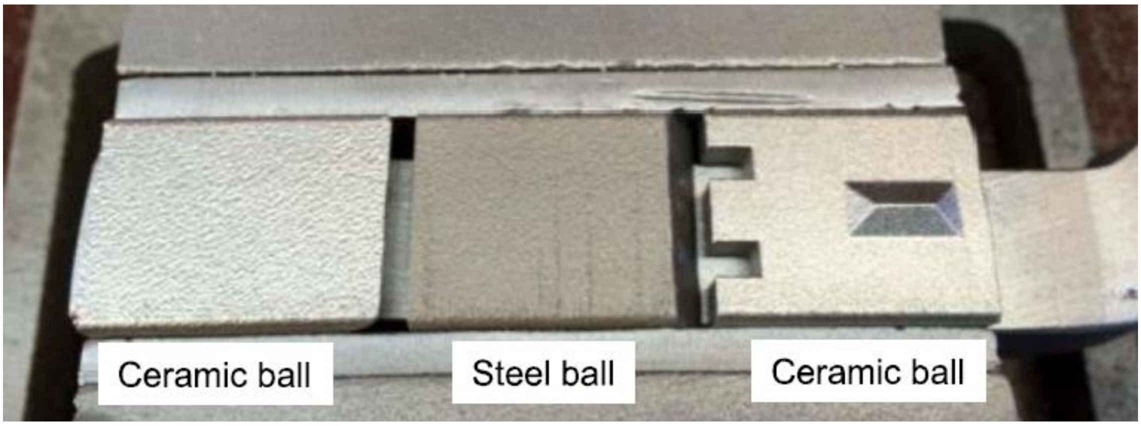

Figure 10. Parts processed with different shot peening materials

The main use of shot peening is to improve the surface quality. AM machine manufacturers recommend multiphase shot peening with different materials to achieve the best result. The figure 11 below shows parts before and after shot peening.

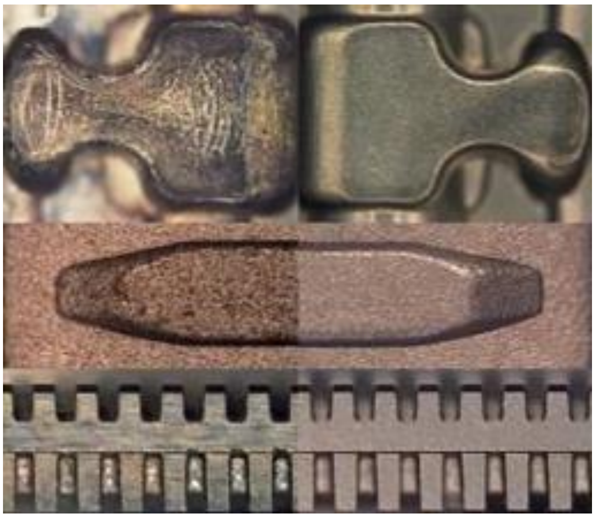

Figure 11. Metal part before and after shot peening (Nonabrasive Cleaning N.d.)

3.3.4 Abrasive Flow Method (AFM)

According to Kumar & Hiremath (2016, 1297) AFM was developed during 1960s by Hone Corporation of USA to enable producing nano level surface finish to products that have complex internal features difficult to machine by traditional manufacturing methods. It is based on abrasive media that is extruded under pressure through internal features (figure 12). AFM can be classified into three types:

1. **One-way** where media is extruded in one direction
2. **Two-way** where the movement direction of media is changed during process
3. **Orbital** where small vibrations are added to system

Within industrial components AFM is used to process for example bevel gears which are produced conventionally. Casting process and cutting process leaves small burrs which detach and end up to non-desired places. Using AFM the industry can overcame the issue. (Kumar & Hiremath 2016, 1302.)

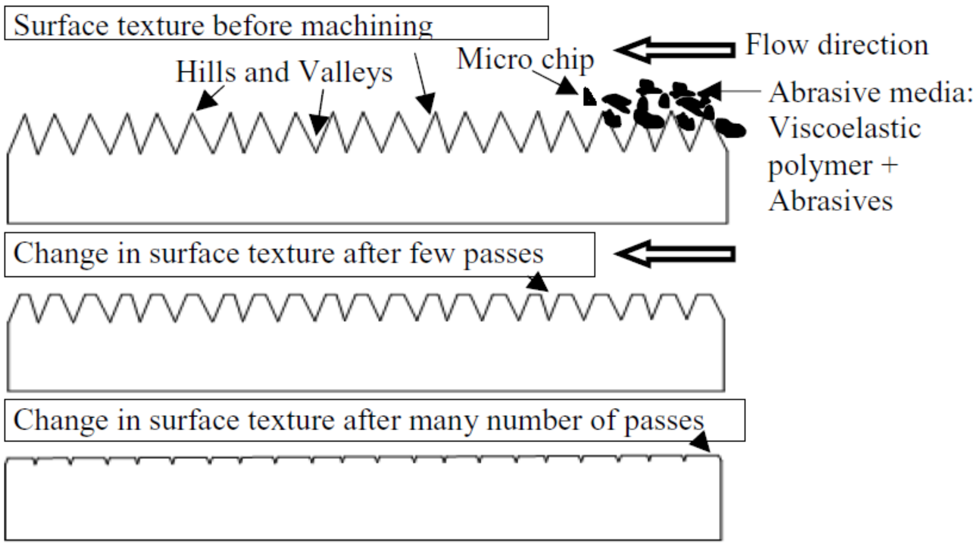

Figure 12. AFM material removal mechanism (Kumar & Hiremath 2016, 1298)

3.4 Available materials

According to Gibson and others AM was originally developed to support polymeric materials, waxes and paper laminates. Later composites, metals and ceramics are introduced to the market. (Gibson and others 2014, 10.) At the moment AM machine suppliers develop materials to satisfy industry needs. Typically powder materials are produced trough gas atomizing process. Every machine supplier has their own material supplier, characteristics and commercial names for materials which makes comparing hard. Still AM materials imitate the same characteristics as typical from traditional manufacturing methods. The table 1 below shows AM machine manufacturers and materials they provide.

Table 1. Available materials according to AM machine manufacturers

		Aluminum	Tool steel	Stainless steel	Nickel alloys	Titanium	Cobalt/-chrome	Copper
Sciaky INC.	EBAM	X		X	X	X		X
Optomec	LENS	X	X	X	X	X	X	X
Ex One	BJ			X	X			
SML Solutions	SLM	X	X	X	X	X	X	
Additive Industries	SLM	X	X	X		X		
EOS	SLM	X	X	X	X	X	X	
Desktop metal	BMD		X	X				X
3DSystems	SLM		X	X			X	
Concept laser	SLM	X		X		X		X
Arcam EBM	EBM					X		

The Finnish companies that provide metal AM services tend to have the same basic materials to choose from. Swedish global engineering group Sandvik Osprey produce atomized metal powders for metal AM and they provide many types of stainless steels, tool steels, low alloy steels, copper alloys, cobalt alloys and other types like maraging steel and Ni-based alloys. The product database consists over 1000 different alloys and typically over 400 is available straight from stock. (Metal powder alloys N.d.). According to Sandvik's sales and marketing manager the powders can be manufactured very broadly but the more difficult question is whether the alloys can then be processed effectively in AM. The work required to qualify and optimize alloys for the AM can be significant and depends to a largely on the intended application. This is reflected to the relatively limited range of alloys in the market. Also, current AM materials imitate the materials used with traditional manufacturing methods and are not necessarily optimized for AM but new alloys specially designed with AM in mind are expected to appear as the technology matures. (Murray 2018.)

3.5 Material behavior under load of SLM produced parts

Multiple studies are made for different materials considering the fatigue and fracture behavior. Each study relies on specific manufacturer so the results are not necessarily comparable and generalizable. In this work the main principles are presented of high cycle fatigue and fracture behavior of AlSi10Mg and fatigue crack growth behavior in 316L which are both performed using SLM technology.

Brandl, Heckeberger, Holzinger and Buchbinder (2011) studied additive manufactured AlSi10Mg samples using Selective Laser Melting. The purpose was to investigate how the build orientation, heating of the building platform and post-heat treatment effects to high cycle fatigue and fracture behavior. The used machine was Trumpf TrumaForm LF130 powder bed machine. Sample parts were produced in three different angles: 0°, 45° and 90° as show in figure 13. The building platform was either heated (300 °C) or non-heated (30 °C).

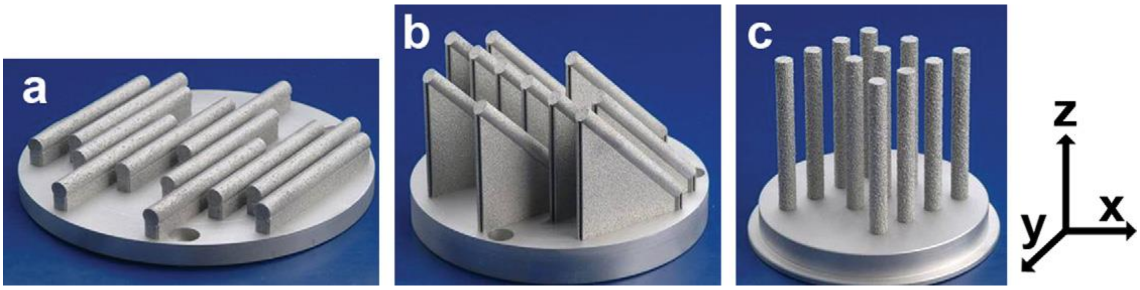

Figure 13. Tested AlSi10Mg rods in different build directions (Brandl and others 2011)

The study shows that imperfections such as porosity has great effect to fatigue resistance. The building direction was the only difference in manufacturing process so it can be seen as the main reason of imperfection after printing process. Parts printed to 0° angle (a) obtained the best results before peak-hardening. Still the building angle did not have as great impact as peak-hardening had. After 6 h at 525 °C and room temperature water quenching the microstructural difference is not apparent any more. The conclusion was that the heat reduces imperfections and microstructure becomes homogenous. Still the samples built at 30 °C and 0° angle showed higher fatigue resistance than in 45° and 90° angles. To increase the fatigue resistance and the static tensile strength the combination of 300 °C building platform and peak-hardening were concluded to be the most suitable processing. (Brandl and others 2011.)

Other study was investigating the fatigue crack growth behavior in 316L stainless steel manufactured by selective laser melting. The study showed that stress relieving heat treatment has no significant effect on characteristics of SLM-produced 316L and it reaches good fatigue performance in as-built condition. The ultimate tensile strength was 565 MPa as build and 595 MPa with heat treatment of 2 h at 650 °C under argon atmosphere. Literature values show range between 530 and 680 MPa. Yet the building direction seemed to have an effect to progress of the crack (figure 14). Crack progressed faster when layers was perpendicular to crack direction (a). (Riemer, Leuders, Thöne, Richard, Tröster, Niendorf 2013.)

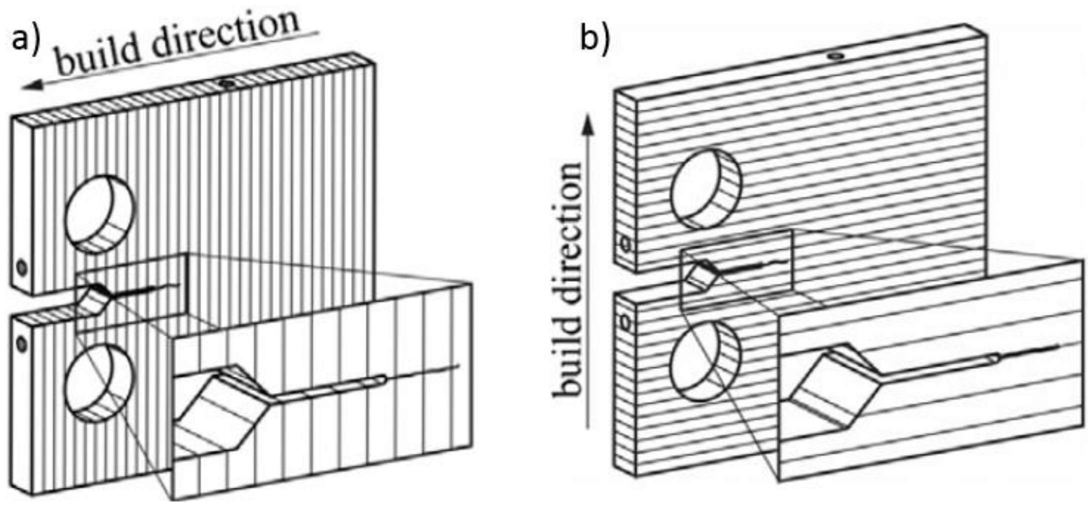

Figure 14. SLM building direction effect to crack behavior

According to Traff (2018) the powder bed fusion technology reaches the same properties as with traditional casting. Still the parameters, powder quality, post-processing and many other factors have a significant influence. Typically, machine builders guarantee specified material characteristics with their process parameters.

3.6 Development of costs

High cost of AM has been one of the main retardant factor for the development. Systems designed for industrial use with considerable building volumes are easily over 500 000 € and require additional tools and software's to work effectively. For now, the industry has surveyed the sustainable applications and hype phase is passed. Siemens has forecasted that the AM will become 50 % cheaper in the next five years

(Zistl N.d.). This is resultant of many factors but the biggest is the increased competition among AM machine builders. As an example, Alonen, Alonen and Hietikko has listed ten new technologies that different companies integrate and develop.

The same fast development direction has forced AM machine suppliers to take the productivity to the next level. Conventional manufacturing methods tend to be more productive in general but AM methods are catching the distance with big steps. Siemens estimated productivity will increase 400 % from 2013 to 2018 and 200 % from 2018 to 2023 (Zistl N.d). According to Traff (2018) by developing the parameters and process for each project the productivity can be improved. With two years of working the metal printing team in Sundsvall have decreased the printing time to 50 % from the original achieving the needed material properties. In their case the manufacturing of segment molds for refiners is 50 % cheaper if compared to traditional methods. Both decreasing purchasing cost and increased productivity will make AM more competitive against traditional manufacturing methods.

3.7 The future of AM

At current state, many factors are limiting the suitable applications. These factors are for example the size of the building chamber, printing speed, need for support material, post-processing needs and dimensional accuracy. Big growth expectations attract new companies to the industry and the competition will increase. This leads to quick development steps. According to forecasts the building chambers volumes are going to be over triple as big as now with SLM technology. The upcoming changes vary widely between different technologies but the trend is clear. This means more applications can be considered and beneficial. Inquiry directed to research institutes shows that every AM technology will increase the printing speed from current state. FDM methods will reach the speed of 25 000 cm^3/h by the year 2028. Metal selective laser sintering will be capable to 200 cm^3/h after year 2025. Material costs will probably decrease 60 % by the year 2025. All these would mean that total costs will decrease approximately 32 %. (Salmi & others 2018, 43-44.)

Figure 15. Engine nozzle in as build state with complicated geometry produced by Matsuura hybrid machine

In many applications, the AM process alone is insufficient to provide satisfactory functionalities. Therefore, post-machining is required but most of the conventional machines does not support the complex geometries which lead to inconvenience. Machine builders have noticed the gap and started to develop hybrid machines with both functionalities. For example, DMG Mori has developed hybrid machines which has metal direct energy deposition AM technology and five axis milling operation (Lasertec 65 3D Hybrid, N.d). Mazak has similar machine Intergrex i-200S but with turning operation instead of milling (Hybrid multi-tasking machine-AM, N.d). Both are capable also to add material to existing parts and work with different materials. Not only DED methods are used in hybrid machines but also powder bed fusion technology. Matsuura has developed Lumex Avance-60 hybrid machine that is based on powder bed technology and milling operation combined. Building chamber is bigger than in average AM machines (600 x 600 x 500 mm). Milling is used every couple layers to directly machine the part during AM process so parts have machined surface as in build state (figure 16). The company claims they have increased the building speed to 35 cm^3/h. (Lumex Avance-60 N.d.)

4 Design for Additive Manufacturing (DFAM)

As stated before the additive manufacturing offers new possibilities for the geometry. Still the method is not free from designing rules and guidelines to follow to accomplish successful parts. At many cases the manufacturing method set limitations that can be avoided by a correct designing. Every specific AM method has their own characteristics and some may overcome described problems inherently. In this work the design rules for SLM technology are presented and the principles were used during the experimental study.

4.1 Self-supportive geometries

In 3D printing the part is usually printed layer by layer from bottom to top. Therefore, hanging geometries and bridges causes challenges. This is solved by printing support material that is removed afterwards. With plastic part the removal process is rather easy and at some cases the material is different than the actual part and can be dissolved chemically. With metal the matter is not so straightforward because chemical removal by dissolving is not possible with every technology and mechanical removal with tools has an impact to surface quality and increase amount of labor work.

Self-supporting geometries can be used to avoid support structures. Figure 17 below shows the original design colored red with a danger of overhanging without support structure. The problem can be fixed by creating a chamfer. The bigger the angle between building platform and the inclined side the better the outcome is. Creating fillet would also be helpful but still the danger of overhanging occurs with large radiuses because the down-facing unsupported area increases (light red). With same principle, large round internal channels are tricky to make but if the geometry can be changed to remind oval (light red) or even droplet (green) the manufacturability increases. These rules can solve most of the overhanging issues. As a conclusion, there is no need to be afraid of support material but with decent designing is possible to prevent unnecessary ones.

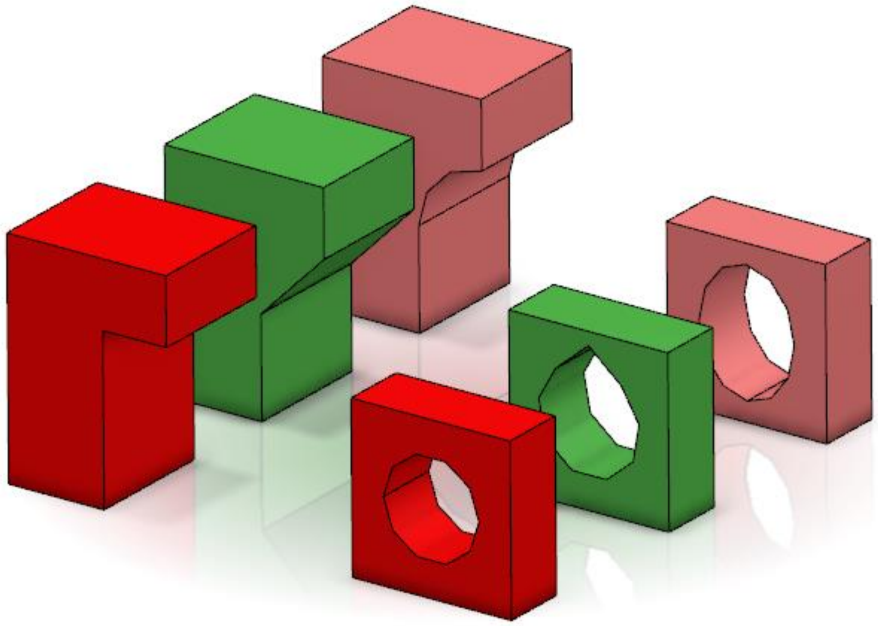

Figure 16. Self-supporting geometries for overhanging and holes

As said, 45° chamfer can be built without bigger challenges with SLM machine and is the most suitable solution when the length of the side is limited. If length is not limited the designer should prefer larger angles.

4.2 Part orientation

According to Thomas (2009, 160-161) surfaces under angle 45° require support structure. The support structure does not improve the surface roughness but make the building possible. The down-facing surfaces has more problems than up-facing surfaces as shown in figure 19. The optimal surface for both down-facing and up-facing surfaces would be 90°. If some surface is important for functionality it should be build facing up with 0-degree angle.

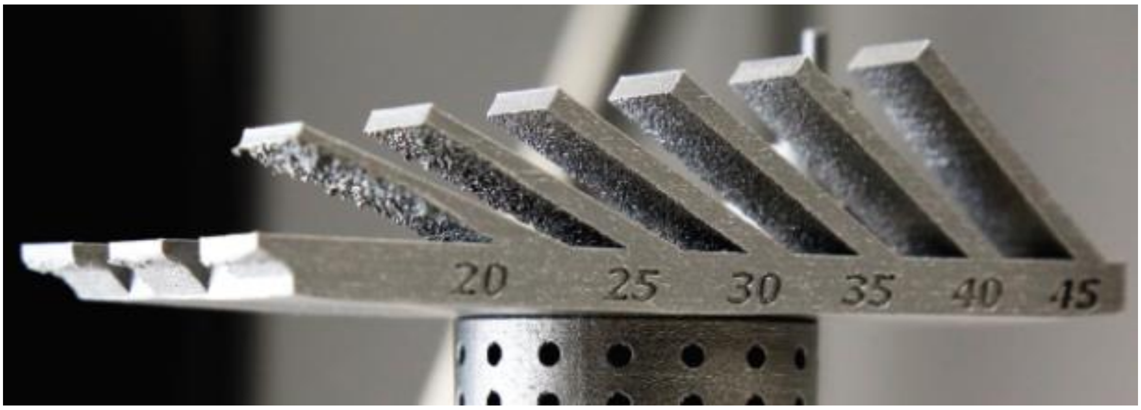

Figure 17. Surface roughness of down-facing surfaces (Southway 2017)

Up-facing surfaces are expected to be dimensionally accurate but still uneven. If needed the 0.3 mm of extra material can be added and machined afterwards to have dimensionally accurate smooth surface. Side walls should be flat and within ± 0.05 mm so no extra material is needed if tight tolerances are not demanded. In that case 0.12 mm material can be added. With down-facing surfaces there is not underlying material to print on. This leads easily to a convex surface shape which need to be machined in case down-surface is critical. (Thomas 2009, 162-163.)

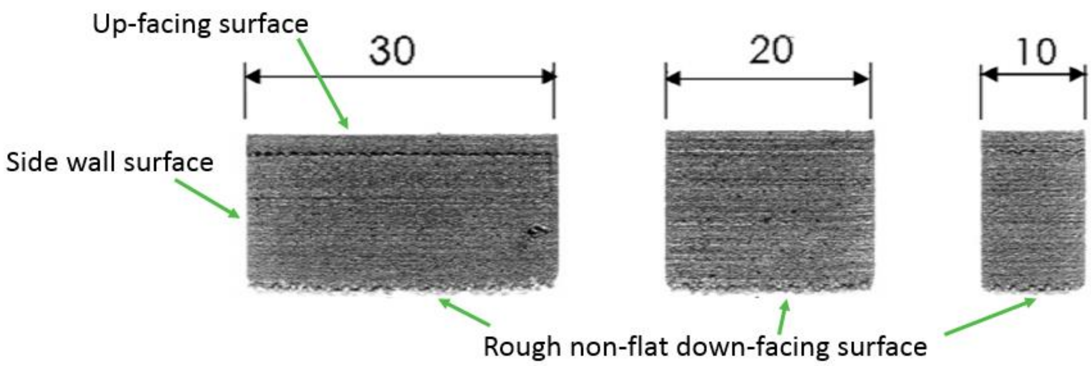

Figure 18. Illustration of surfaces and down-facing surface with convex shape (Thomas 2009, 163, modified)

On the other hand, the part orientation can be used to avoid the support material. In the figure 20 a complex geometry pipe (colored blue) is placed in two different ways: down face against building platform and down face downwards with a small angle.

The amount of needed material was decreased by 40 %. With the same change the amount of post-processing decreased significantly because internal shapes did not need support structure.

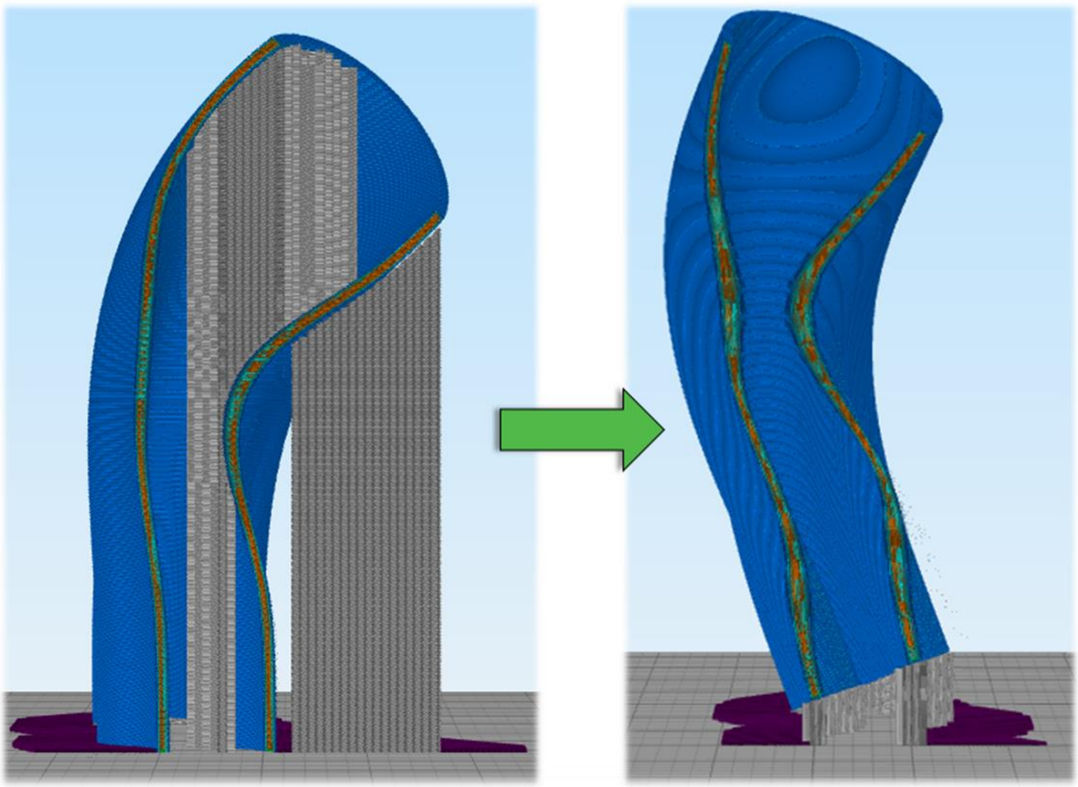

Figure 19. Section view of part orientation effect to support material usage (blue=part, grey=support material)

Building direction does not only have an effect to planar surfaces but also cylindrical shapes as holes. The smallest hole that can be built horizontally without support material is Ø 1 mm. Smaller holes will lose their shape because of sagging. The largest hole horizontally is Ø 7 mm. Larger holes will suffer from distortion and need support structure. Smallest hole to be built parallel to building platform is Ø 0.7 mm. Smaller diameters will not be holes anymore in as built state. (Thomas 2009, 174-175.)

4.3 Deformations

Depending on the used AM technology the shrinkage of the holes may occur. Deformations depend on the technology, materials and used parameters. Thomas (2009, 91-93) tested the minimum gap thickness to be 0.3 mm. Figure 21 shows that the 0.3 mm gap is barely visible. These results are only valid when the building direction is vertical to building platform. If angle is changed the minimum gap will increase because down-facing surface is not build on top of solid material. Minimum wall thickness is defined by the capabilities of the SLM machine and 0.4 mm is the thinnest wall that can be produced.

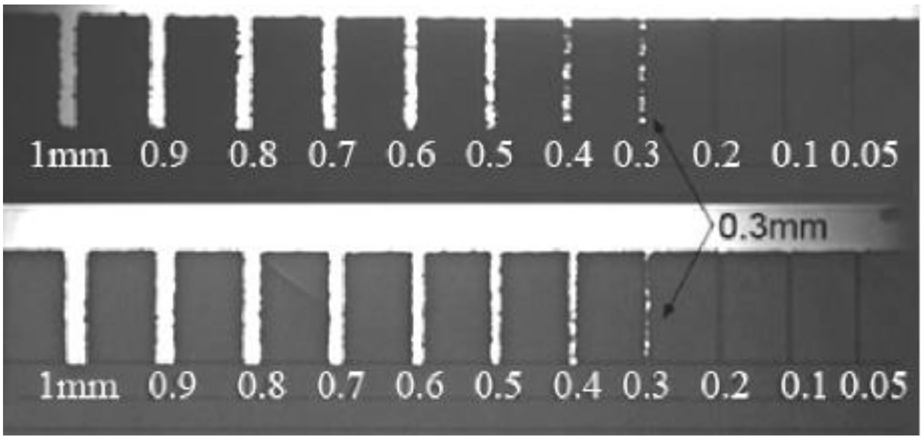

Figure 20. Shadowgraph pictures of minimum gap thicknesses with cylindrical and cuboid pillars produced with SLM process (Thomas 2009, 93)

5 Determination of costs

The cost estimation works as a tool for decision making. The costs must be considered in the early stages of surveying potential applications for AM. In general, the cost of AM parts are economically profitable if the parts are small, has a complex geometry and manufacturing amounts are small. Before more detailed cost estimation process the estimated benefits of AM must be significant. (Alonen, Hoffren, Kesonen & Urpilainen 2015, 66.)

5.1 Cost models

There are a few cost models that estimate the cost of AM parts. Hopkinson & Dickens (2003) presented Analysis of Rapid Manufacturing - Using Layer Manufacturing

Processes for Production -report which aims to evaluate the cost of AM versus injection molding. The study relies on three assumptions:

1. Only two parts is produced the whole year
2. The machine is used with maximum volume
3. The machine operates 90 % of time.

The costs were broken into three categories: machine costs, labor costs and material costs which were divided by the total amount of produced parts. As a result, they discovered that with the injection molding the part would cost 0,23 €/pcs and the same part produced by laser sintering machine (EOSP360) was 2,2 €/pcs.

For this work the calculation method was too simple and did not consider for example the energy consumption because its impact to the end price was under 1 %. The costs per part was not depending on the produced amount which does not give reliable understanding of the true costs. Also, the basic assumptions were set to correspond high series production and the variation of the parts did not occur although AM is usually used for small or middle-sized batches.

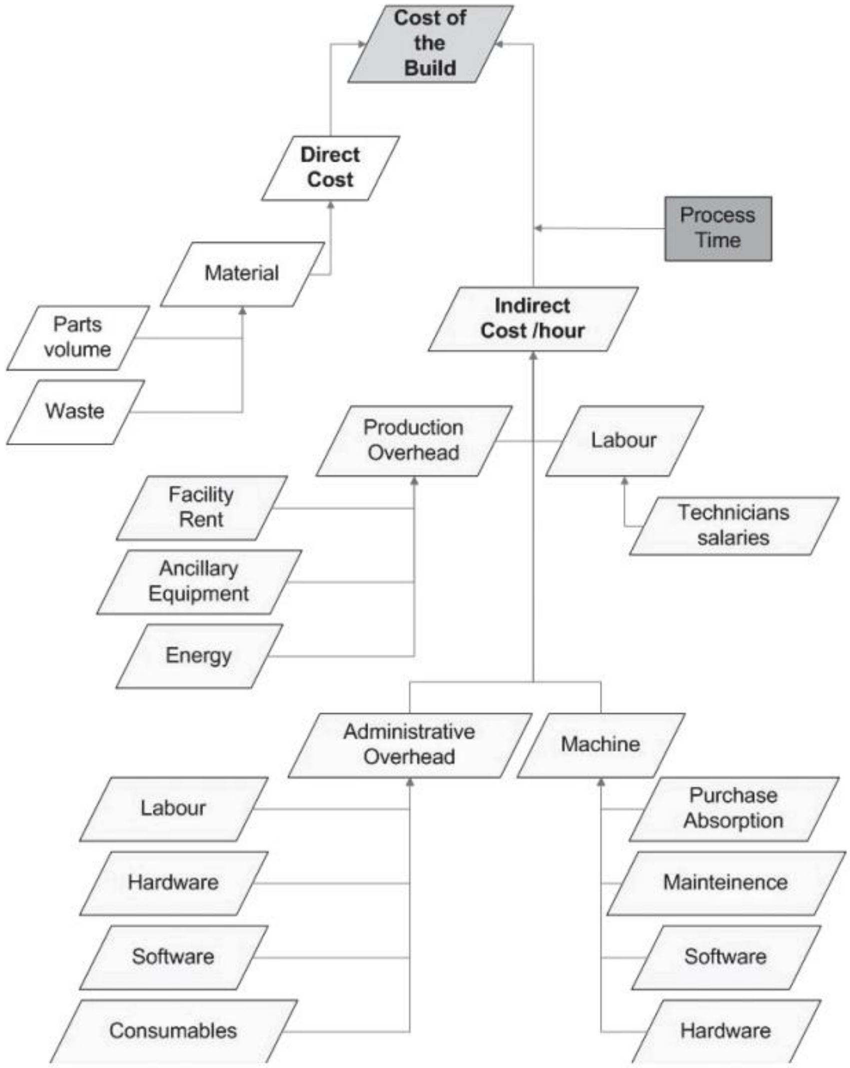

Figure 21. Cost model (Ruffo & others 2006)

Ruffo, Tuck & Hague (2006) made similar study but based it on of the benefits of AM: to produce different components simultaneously. They have divided the costs to direct and indirect costs as illustrated in figure 21. According to Ruffo & others (2006) the Hopkinson & Dickens model was inaccurate for low production volumes and might lead to misleading results because the new model produced 55 % higher price per part.

In this work the cost estimation will follow the main principles presented by Ruffo & others (2006). Still, Valmet was considering both purchasing own metal AM machine and purchasing the parts from subcontractor to find out the best option from total cost of ownership point of view. The costs were calculated to parts designed in experimental study.

5.2 Direct and indirect costs

Different costs are divided into two main categories: direct and indirect costs (figure 22 below). Direct costs were calculated straightly to hourly cost and indirect costs were directed to each work. The needed information for calculation were collected by interviewing professionals. The leasing contract calculation was based on real-life information from Valmet Sundsvall case. Machine purchase scenario was based on interviewing local supplier 3D Formtech that had lately purchased EOS M290 machine. Sub-contractor information was gathered from received quotes. Different scenarios were unified by using same initial data. For example, lifetime and residual value were set to same in every scenario. The calculation method and formulas were checked by Valmet's business controller. The calculation tool is presented in appendix 4.

Direct costs (hourly machine cost)	Indirect costs
- Machine depreciation	- Material costs
- Labour	- Energy
- Softwares	- Inert gas
- Mainenance	- Post-processing
- Facility cost	
- Other acquisitions	

Figure 22. Direct and indirect costs in machine purchase and leasing contract situtations

In addition, several other variables were taken into account. For example, starting cost for each work was estimated to take one hour and included preparing the machine, possible material change and preparing the print job. Total yearly cost was divided with assumed productive time which was also based on Sundsvall experiences. Inert gas flow and cleaning of the machines consume unused material so material scrap rate was included.

5.3 Sub-contractor scenario

To evaluate the profitability of investment the possibility to use sub-contractor needed to be taken under estimation. Companies were searched and eight were included to bid inquiry process (figure 2). All the companies but one used SLM technology which used binder jetting. 3D Hubs and Star Rapid offered web based calculation tools for cost calculation which were used as such. The prices included only the printing process and no post-processing. Material was the same stainless steel 316L. The prices were asked to the experimental study parts designed in chapter 7. Experimental study.

Company	Country	Technology
3D Formtech	Finland	SLM
3D Step	Finland	SLM
AM Finland	Finland	SLM
3D Hubs	USA	SLM
Sculpteo	France	SLM
Star rapid	China	SLM
GPI Prototype	USA	SLM
Shapeways	USA	BJ

Figure 23. Companies used to have the pricing information

6 Survey of potential use

In this work the survey of potential use was done without prejudice by involving personnel as much as possible. Internet inquiry was the base of surveying and produced both specified parts and general ideas. Interviewing was used to become more familiar with each idea, gain better understanding of general ideas and specify them. The observation was used by two different way: visiting different production sites and during appointments with participants.

6.1 Internet inquiry

According to Kananen (2017, 78) the main threat of internet inquiry is low response rate. In this case the motivation and lack of time were considered to be the most significant reasons not to answer to the inquiry, so a reward was organized. Every person that answered to the inquiry was rewarded with a free doughnut which leaded to considerably high response rate as presented in the results.

Additionally, the internet questionnaire offered many strengths to improve the reliability. All the participants answered to the same questions. The participants could select a suitable time for the answering and the answering process was free of stress and criticism.

It is not easy task to answer to questions that consider different challenges that we are used to solve every day. The participant might feel that this is not relevant or interesting and they have nothing to say. To solve this problem and to add meaningfulness to the inquiry a presentation was organized. The presentation included the basic theory of AM and the possibilities and limitations of the manufacturing methods. Multiple examples, pictures and references were shown and the main idea was to plant a thought about what could be the potential applications for metal AM in their own work. Also at the end of the presentation the audience heard how the research will continue so they could prepare.

The questionnaire was created on Webropol platform which offer tools to arrange and analyze internet inquiries. The inquiry is visible in appendix 1. The inquiry was divided into three different parts to serve specific purpose. The first part was to teach the participant to answer and identify them by the organizational group (questions 1-3). The second part was to survey the general attitude towards metal AM and recall the possibilities and limitations of the technology. The questions were quantitative multiple-choice questions to help analyzing (questions 4 and 5). The third and last part included open questions and all the actual ideas were supposed to be listed into open fields (questions 6-13).

6.2 Target group

The target group of the questionnaire was limited to technology and engineering groups from different sections. The participants had expertise mainly in design engineering and development engineering. Also, product managers, process specialists and concept managers were involved to have wide understanding of the parts and assemblies. At total five groups were included and total number of participants were 78 persons. It could have been possible to send the questionnaire to a larger group but it was seen unnecessary for the number of ideas. Presumably the larger group would have leaded to greater number of ideas but many of the ideas would have been similar to each other.

6.3 Limiting the potential applications

As the purpose of the work was to recognize whether the metal AM is useful for Valmet Rautpohja the limiting the ideas was seen as one of the most important phases. By selecting wrong applications, the conclusion of the suitability in the end would be wrong. This was recognized and discussed in weekly meetings with supervisors. General method to proceed was agreed and main evaluating criteria were selected. The method to evaluate the potential applications was similar to Trade-off Methodology Matrix (TOM) presented by Lindemann, Jahnke, Reiher and Koch (2014, 939). It is used to screen whether the AM enables benefits for considered part. The evaluation process was divided into three main parts: part definition, preliminary selection and final trade-off. In every section of TOM were structured and divided into sub-categories.

The questionnaire answering time was rather long period because presentation was held in three-week timeframe and proper answering time were provided to each participant. To speed up the process, grouping of the ideas was started before the questionnaire phase closed. The ideas were tabulated (appendix 3) and parts were defined with help of personnel involved to the questionnaire and product owners. With some applications, the ideas were expanded to product families and in some other ideas were narrowed to contain smaller entities. Following information were used to define every idea:

- Picture
- Responsible person
- Functional unit
- Reference to drawing or part number
- Size (main dimensions)
- Estimated yearly consumption (1-10, 10-100, 100->)
- Estimated production cost (low, moderate, high)

Ideas were grouped to six main groups: brackets/spacers/holders, flow parts, assemblies, parts, big parts and other entities. At first, comparing single parts against assemblies felt unfair and assemblies were assumed to prosper better. Still the evaluation was made for parts and assemblies mixed and results show that ideas were not unequal because the evaluation criteria was designed to allow general thinking.

In this work the preliminary selection was used to limit out most of the ideas using evaluation criteria. Six criteria were enough to dismantle the idea group and form preliminary rank order (listed below). Criteria were based on gathered theoretical background information and correspondence was evaluated with scores from 1 to 3 with help of part definition information. The preliminary selection gave an answer to question whether the idea was suitable for AM or not. The sixth criterion was not professional but still valuable because with only five criteria the ideas were not ranked enough and scores were too close to each other. This offered a possibility for supervisors to affect to idea selection decisions but still did not ruin the justifiability of the evaluation.

Used criteria for and weights in preliminary selection:

1. Estimated cost with traditional methods 0,15
2. Size (is it printable?) 0,1
3. Complexity of manufacturing and assembly 0,2
4. Complexity of geometry 0,2
5. Property improvement 0,25
6. General “gut” feeling 0,1

Not every of the criteria were seen as equals so weighting multipliers were created. Property improvement was the most important because additive manufacturing offer new possibilities for designing so it had the highest weight 0,25. Complexity of manufacturing and assembly and complexity of geometry were seen equally important and the weight was 0,2. The lowest weights went to size and general gut though (0,1) because the manufacturing technology is developing and machines can print bigger parts in near future. With these criteria and weights, the ideas were narrowed to ten most potential and rest of the ideas were limited out from final trade-off phase.

6.4 Final trade-off

Previous phase limited out 76 % of the ideas and only ten most suitable applications for printing were remaining. All these can be considered for further development but in this work time resource allowed focus only to two. On the other hand, it would be beneficial for the company if they have a list where to select suitable applications to consider. Therefore, a ranking was made with supervisors including new evaluation criteria and weights (listed below). In this phase the criteria highlighted possible benefits, cost reduction and manufacturability with AM methods. Suitability regarding present goals and projects was also taken into an account to lead this thesis more to co-operation with other employees and enhance current projects.

Final trade-off evaluation criteria and weights:

1. Manufacturability with AM methods 0,15
2. Material consumption 0,15
3. Decreasing number of parts 0,2
4. No need for post processing 0,15
5. Achievable cost reduction 0,25
6. Suitability regarding present goals/projects 0,1

After evaluation, the ranking was ready and results discussed with supervisors. It was agreed to select two ideas to develop further. Selecting ideas that ranked first and second would have been easy choice but they were so alike to each other that it would not be useful to develop them. It was agreed to select ideas that differ from each other to obtain the highest possible usefulness. Idea with highest scores included a lot of aspects to develop. It was also a new innovative idea that came from previous student work. Idea with second highest scores was similar to the first. The third idea was completely new application so the weight of the history was negligible. The fourth idea was a part with high load resistant requirements and volumes. The only thing to study was the coating method. The fifth idea was a nozzle pipe with complex internal shape. With this information the ideas that ranked first and third were selected for further development. From now on the first ideas are called “Flow manifold” and “Tail blower”.

7 Experimental study

The purpose of experimental study was to tryout two of the best ideas and evaluate the succeeding of idea screening process. Also, the parts were supposed to proof the concept of AM being one serious manufacturing alternative. The experimental study follows mainly the next five steps: create list of requirements, define the goal and developing approach, design the parts additive manufacturing in mind, manufacture prototype if possible and evaluate. Limited timeframe and highly specialized applications guided the design more to a development of a concept that benefits from AM rather than a detailed design.

The list of demands did not limit only to requirements. Function of the whole assembly, interfaces, earlier optimization history and function of the core part were taken into an account. The requirements list template was created and fulfilled with product manager and supervisors. Lists for both cases are seen in appendixes 5 and 6.

Manufacturing costs evaluation was done using cost analysis tool presented in chapter 6 Determination of costs. Printing times were evaluated with softwares provided by machine suppliers in co-operation with 3D Formtech and Valmet’s additive design engineer Henrik Traff. Both manufacturing costs and printing times are presented in the results.

7.1 Case 1: Flow manifold

The end use of flow manifold was classified information so the design process is described at very general level. Flow manifold was a part that guide mass flow to feeders with specified speed. At current state the same function was done by an assembly containing many parts that require a lot of manual labor because of the complex geometry and high surface roughness tolerances. Typically, only the grinding work takes 30 to 35 hours' manual hand work. At the same time the flow is not optimal and power loss causes energy inefficiency.

The first idea to replace the existing parts with printed one came from student work 2017. The likeness model (figure 24) was already created and formed a base for further development. The model was not designed for additive manufacturing and no flow optimization had been done. For this work these two main aspects were under development: redesign the model to be printable and develop the flow characteristics. Not only the printing process needed to be considered but also post-processing. According to requirements list the interior of the part must be grinded to surface roughness Ra=0.4 µm which is at current state accomplished by hand grinding.

The likeness model included 6 parts (header, mounting plate and four sleeves). In an ideal situation, the same characteristics could be managed by single part so one part instead of six was selected as goal. Manifold needed to spread the mass flow evenly to four outlets. With the likeness model the sleeves were different size and therefore limited the flow.

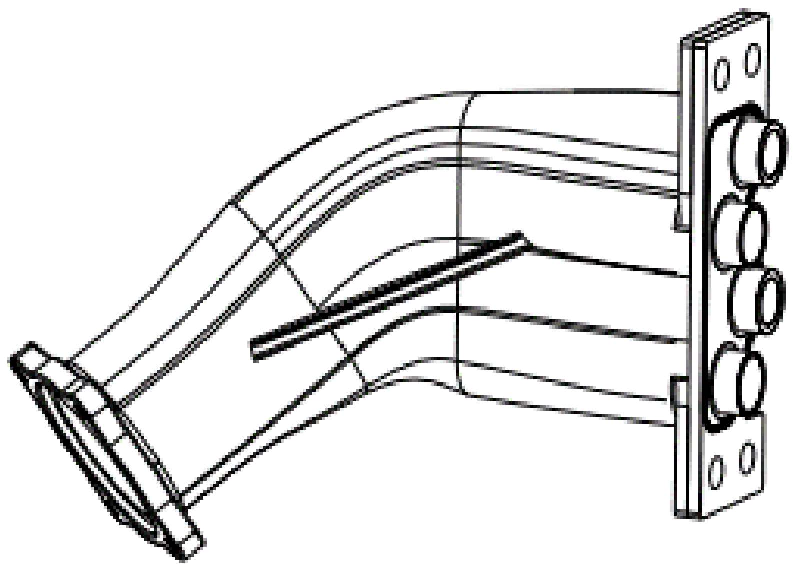

Figure 24. Likeness model of concerned flow manifold

7.2 Designing process: Flow manifold

Designing started by modelling the input and output interfaces. The interface surfaces needed to be precise and even so post-machining was required. Connection to input pipe was designed to standard flange. Threads could have been possible to manufacture with AM methods but the accuracy would have been questionable and therefore, through holes with machining margin were designed. Connection to a counterpart at output side was designed to be with four bolts which tighten the o-ring between the flange and a counterpart.

In the first design round (presented in figure appendix 7) the four outlets were separated from each other. The idea was to adjust the diameter of each pipe to limit the flow and reduce turbulence. With this feature the sleeves were unnecessary. Concept was evaluated with supervisors and a few drawbacks were found. Firstly, a risk of contamination was high in position where pipes separated from each other. Secondly, the idea demanded more material and mass which made the manufacturing expensive. Optional post-processing of internal shapes was harder than in original likeness model. Therefore, the idea of separated pipes was overridden by the original idea.

Focus concentrated back to original model. The main question was which parts should be printed and which produced traditionally. The interface surfaces needed to be machined in every situation. They also needed to be thick and robust which meant longer printing time and higher manufacturing cost. Therefore, the input pipe connection was designed to be welded afterwards. The same challenges took place with mounting flange in another end. This was discussed with 3D Formtech and their suggestion was to use pre-machined billet as a building platform in a AM machine. With that possibility, the flow manifold deployed the benefits from both additive manufacturing and traditional manufacturing. The manifold could be optimized regarding the flow characteristics and mounting flange obtain the needed robustness and accuracy. At the same time the needed printing time was reduced significantly. The general idea is presented in appendix 8. In addition, also flow simulation and calculation were done to discover the flow characteristics versus the current released solution and the results are seen in appendix 9.

Complex internal geometry was not easy to grind and it would have caused problems. Therefore, two different solution were studied: abrasive flow method and different coatings. Possibility to use abrasive flow method was investigated with Tasowheel company which have AFM machine. The part was suitable for AFM but needed complex jig. The machine has been continuously over-loaded and therefore they retreated from the development work. The next possible solution was teflon coating. According to Alu-Releco the traditional teflon coatings are 20-30 µm thick but nowadays there are also possibility to use 500-700 µm thick coatings. Substance is sprayed to the surface and then heat treated between +200 °C and +420 °C. The surface roughness would be Ra 2-4 µm. Rough estimation was that the Teflon coating would cost about 150 €/pcs. (Ruokolainen 2018.) In addition, different coating possibilities were discussed with Tigate Ltd. According to Isoaho (2018) the coating can be added by three different methods: immerse in liquid, injection and molding. In this case, only the injection and molding methods were able to produce coating thick enough. The suitable coating was polyurethane based hybrid thin film coating which offered non-stick surface with good resistant against abrasive consumption.

7.3 Case 2: Tail blower

Tail blower concept was an assembly that would be integrated to current functional unit. The key function of tail blower is to create a flat air spray pattern that causes a head of the paper web to separate from the drying cylinder in a whole width of the paper machine. At current state Valmet did not have own released solution for this but a bit of research and development had been done regarding different possibilities. The idea was based on two different parts: a manifold pipe that goes parallel the machine and sufficient number of nozzles. In an early stage a rough calculation and evaluation were made about the needed number of nozzles. A result was that roughly 50-100 nozzles is needed for 10 m wide paper machine per functional unit, so the weight of a nozzle need to be minimized in order to keep material costs and building time low. The design of the tail blower and manifold pipe should allow paper web to flow over it without getting stuck. Design should also enable free movement of the system to function properly.

7.3.1 Designing process

Before designing process an overview to principles of air flow was made. In the ideal situation, the nozzles would create sufficiently strong and wide flat pattern approximately to 15 cm distance from the nozzle with a reasonable air consumption. Therefore, the geometry of the nozzle plays a crucial role.

The first design was made with a simple idea (figure 25). The air would be guided to air pocket where the pressure evened and then led through small holes. Mounting to counterpart was with two screws. This idea was considered poor because of the big size and poor air covering angle. Also, maintainability would be poor because every nozzle needed to be released in order to remove the manifold pipe.

Figure 25. The first design of flat pattern air nozzle

After creating the first design a research showed that similar nozzles are already available in the market with optimized air flow. Prices varied between 30 € and 130 € per nozzle with stainless steel material. Still the existing designs were not fully suitable for this scenario and a decision with supervisors were made to continue designing an optimal shape for this application. The second design were made smaller and with only one output nozzle. The shape of the nozzle was mimicked from existing flat pattern nozzles to water where a round drilled hole with spherical end V notched outlet (figure 26) cause the flow to spread. To function properly the V-notch and round geometry demanded extreme manufacturing accuracy which was not yet achievable with AM methods without post-machining. Still the small shape was beneficial to AM methods so the first and the second ideas combined could be best for this application.

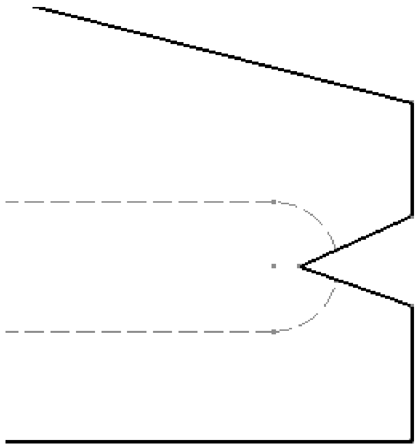

Figure 26. Basic idea of V notched spherical outlet causing water to spread along X-axis

The third design combined the previous ideas (figure 27). A small size and wide outlet worked well with prototypes. The design used the main benefit of AM (freedom of the design) in the most functional parts. The internal flow channel was designed to be smooth and let the air flow freely. Cross-sections were calculated to allow bigger flow in the inlet head and choke the flow in the outlet. Outlet was also curved to be wider from the sides to guide more air to edges and therefore, create wider spray pattern. This was simulated with ANSYS program and results were promising. Mounting to rectangular manifold pipe needed to be quick to install and sealed. A quick connection was designed as illustrated in figure 27. The installation was meant to happen with 90 degrees turn which tighten the O-ring between nozzle and pipe. Manufacturability was asked from local sub-contractor and as expected, they said the unsupported area would cause a thermal conduction problem with metal materials. Also, the needed support material would be hard to remove. Therefore, the mounting needed to be re-designed.

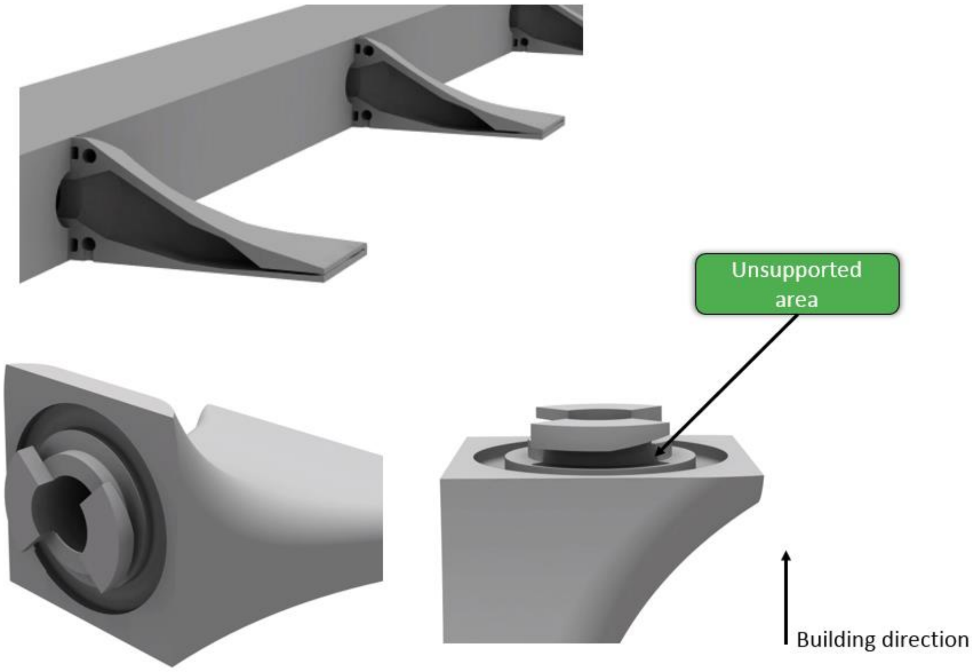

Figure 27. General idea of the third design of flat fan nozzle

The fourth design followed the same principle than the third. Mounting to manifold pipe was executed with self-locking shape. General idea of the locking is presented in appendix 10. O-ring tightens between nozzle and pipe by turning the nozzle specific angle. When the pipe is mounted to counterpart the nozzles cannot separate because rotation is prevented. The final design included also an optional screw mounting to counterpart (figure 28) to prevent structure movement during blowing force.

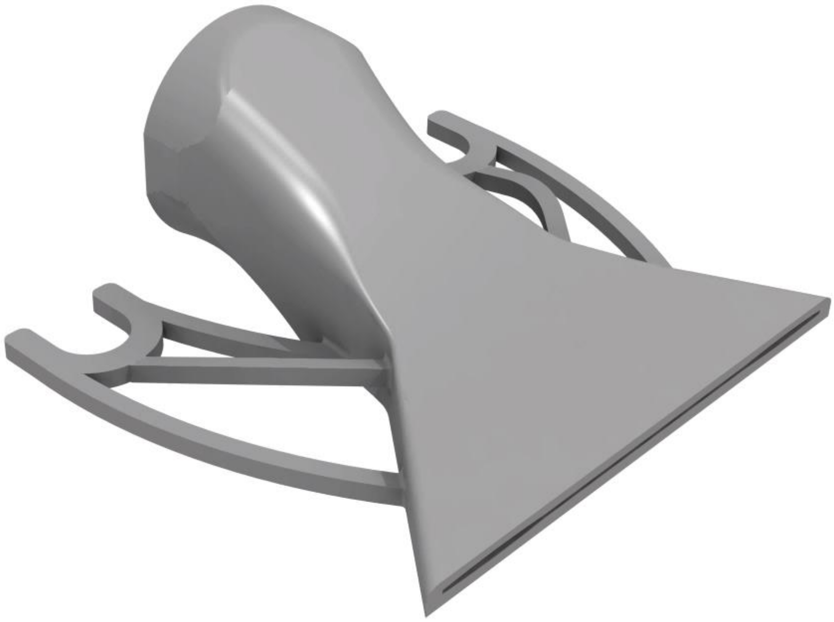

Figure 28. Final design of flat fan nozzle

Air flow simulations were done using Ansys program. Results are seen in appendix 11. The only input value was velocity of the air which was selected to be 50 m/s^2. With that information, the air consumption was calculated by multiplying the speed with input channel area. The results from the first simulation round showed four aspects (listed below with improvements) which were changed to model and the impact was evaluated by the second simulation round:

1. The air pattern spread too strongly to the sides
   Geometry of the air channel was changed
2. The air channel was too open
   Air pocket was created and output channel made smaller
3. The velocity at 5 cm from the nozzle was too low
   The geometry of output channel was changed and velocity increased
4. Selected velocity was too slow
   Input velocity was changed to 80 m/s

7.3.2 Manufacturing the prototype

As the nozzle was rather small part plastic prototypes were made simultaneously with the designing process to find the optimal nozzle geometry (figure 29). The plastic prototypes worked well and spray pattern was easy to evaluate by blowing to the input channel and feeling the spray pattern. Also, the concept of designed quick-lock was experiment with plastic prototype.

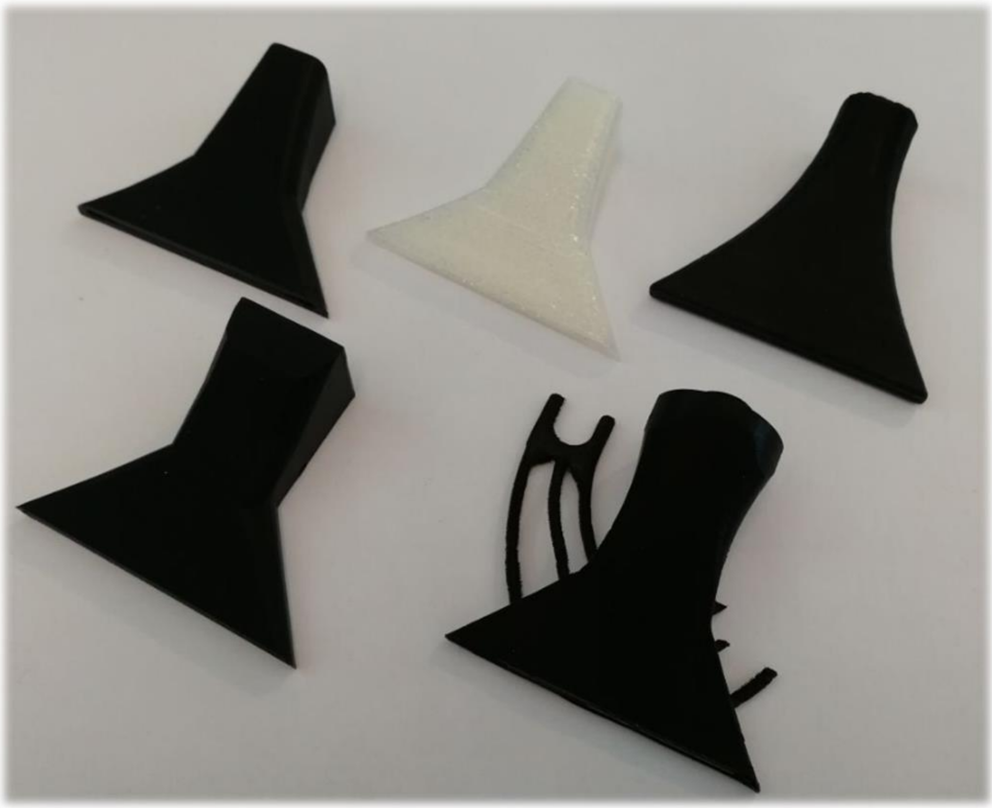

Figure 29. Produced plastic prototypes of flat fan nozzle

Not only plastic prototypes were made but also metallic. A visit to Valmet Sundsvall location was arranged. A nozzle was produced besides of other production so printing time was only a little bit longer and therefore the manufacturing cost was very little. The nozzle was printed in standing position to ensure the internal flow channels and quick-locking shapes to print correctly. Because of the center of the gravity was trying to fall the nozzle a support structure was designed to ensure successful print (figure 30). The output channel height was only 0,4 mm and only partly open. To function properly the channel needed thin tool to clean out excessive material.

Figure 30. Bronze flat fan nozzle produced with EOS M400 SLM machine

7.4 Evaluating the entire concepts

The flow manifold was redesigned and both printability and flow characteristics improved. Still, the goals were not fully filled because the designed flow manifold required five different parts (header and 4 sleeves) plus the welded pipe connection flange. This was the best solution because it offered enough adjustment range and the manufacturing used beneficial features from both, AM and conventional manufacturing. Studied coating possibilities stayed in level of concept and no final decision of the coating solution were made.

AM methods offered completely new approach to tail blower designing and therefore the final design was many ways different than expected. The air flow characteristics were improved with help of flow simulations and possibilities of AM were exploited in many places (self-locking and flow channel). The optimization regarding air pattern, weight and manufacturing costs could be done further. The computational air consumption was reasonable and significantly lower than in competitors existing product. In order to evaluate the functionality of the whole system the manifold pipe and air connection needs to be designed.

8 Results

Presented numbers are changed but ratios are corresponding.

8.1 The most potential applications

The response rate of the questionnaire was 47 % which was considered high. Altogether 37 answers produced 35 categorized ideas and several additional entities (appendix 3) to study further which were dropped out from the evaluation. The ideas were divided into five categories: brackets/holders/spacers, flow, assemblies, parts and big parts. Flow category was clearly the most suitable because 86 % of the ideas in that category ranked in the top 15. Both experimental study cases were also selected from this particular category. Ten ideas with the highest scores are listed below in a general state.

1. Flow manifold
2. Cleaning nozzle
3. Blow nozzle 1
4. Piston element
5. Cable drag chain
6. Blow nozzle 2
7. Guiding element
8. Process adjustment element
9. Special tools
10. Worm shaft assembly

The list shows the most potential applications but does not necessarily mean they are justified. To proof the concepts and evaluate the true suitability of AM experimental studies were made. The estimated manufacturing cost with SLM technology for the tail blower flat fan air nozzle was not significantly higher than the existing products in the market. Printed part costs 94 €/pcs in cheapest case and existing part prices varied between 49 €/pcs and 164 €/pcs. The nozzle created wide pattern and high-speed blow as presented in appendix 11.

The printing costs of the flow manifold was 1750 €/pcs if the part was purchased from AM sub-contractor. Coating, machining, welding and materials were evaluated to cost approximately 1000 € per assembly which makes the total cost to 2750 € per assembly. The released standardized solution costs totally 5891 € per assembly. Every machine with this expansion needs two of the flow manifold assemblies so the possible saving per machine was 6282 €. Additively manufactured flow manifold performed better in flow simulation tests than the present solution (appendix 9). The total pressure was 10 % lower than in released solution and the deviation in output speeds decreased by 57 %. This means the new solution is more energy efficient and produce more stable process.

8.2 Investment profitability review

Manufacturing cost estimation was made in three different scenarios. The distribution of hourly costs between machine purchase and leasing contract scenario are presented in figure 31. Purchasing own additive manufacturing machine would mean lower hourly cost (106 €/h) and therefore also lower manufacturing costs. With leasing contract, the hourly costs were highest during rental time (145 €/h). After the contract the hourly cost drop to 128 €/h. In every case the machine depreciation constitutes the major part and the second significant part was salary of one engineer.

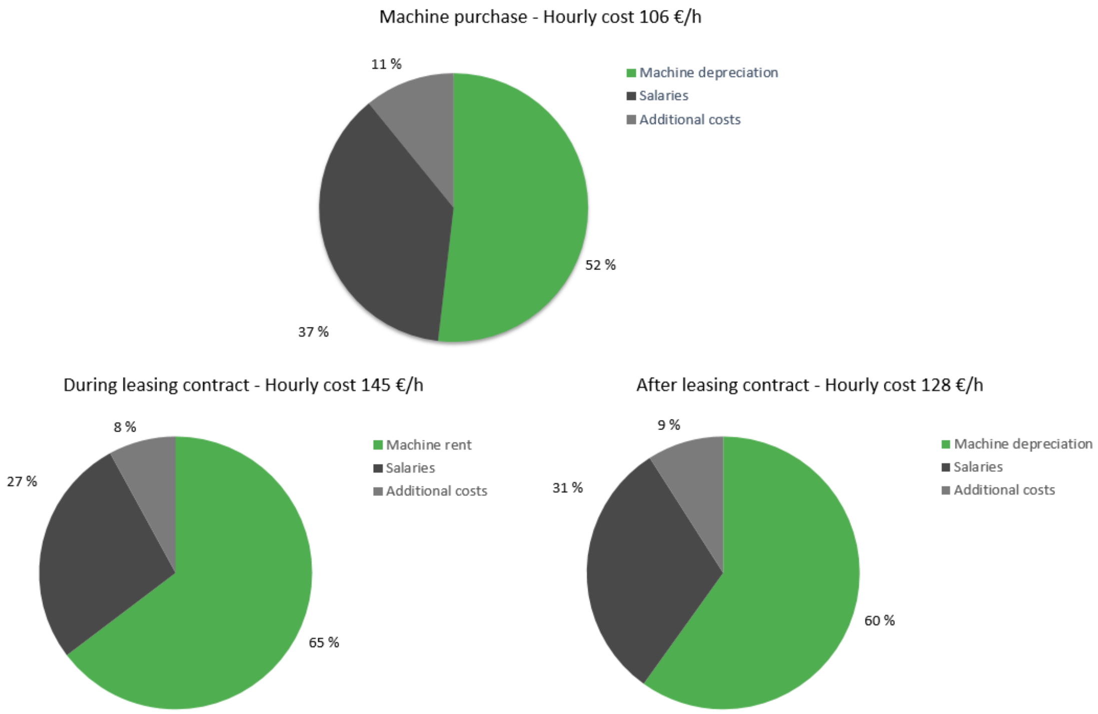

Figure 31. Machine hour cost distribution in estimated investment scenarios

Manufacturing costs in different scenarios of the experimental study examples are illustrated in figures 32 and 33. With small batch sizes the most cost-efficient solution was to use sub-contractor with both cases. Purchasing flat fan nozzles from sub-contractor would be the most cost-effective with any batch size. For example, 72 pcs of the nozzles would cost on average 10 770 € if purchased from sub-contractor and 11 580 € if produced with own machine. If annual consumption is 1000 pcs the difference would be over 11 300 €. These examples were based on average prices from all the offers. With the flow manifold the sub-contractor was the cheapest solution for prototype part and with larger batch sizes the sub-contractor and machine purchase scenario were close to each other.

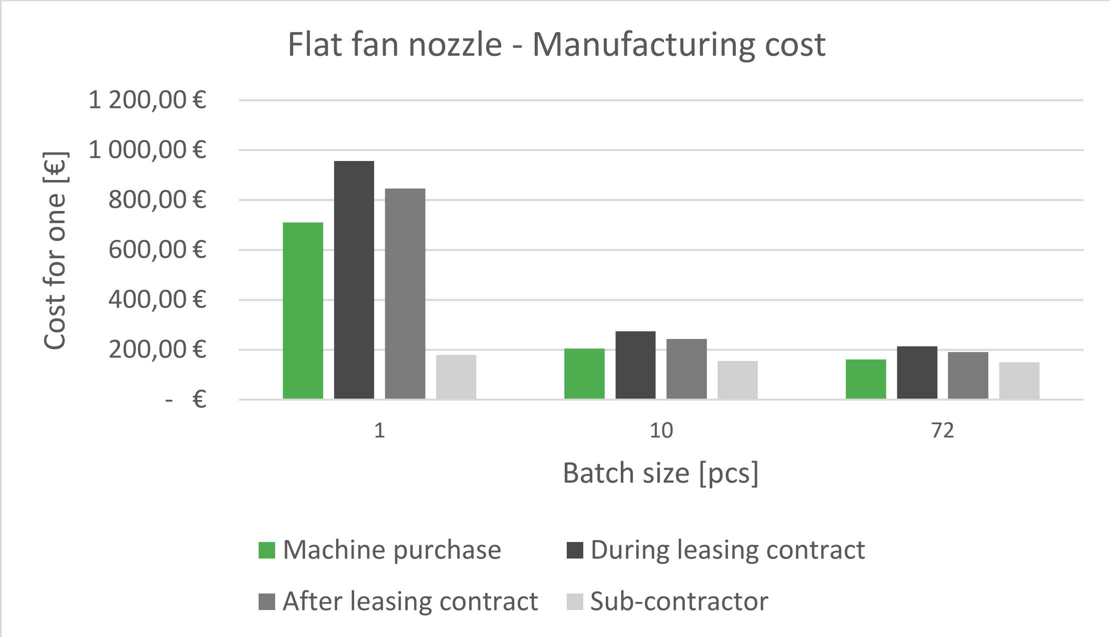

Figure 32. Manufacturing costs of flat fan nozzle

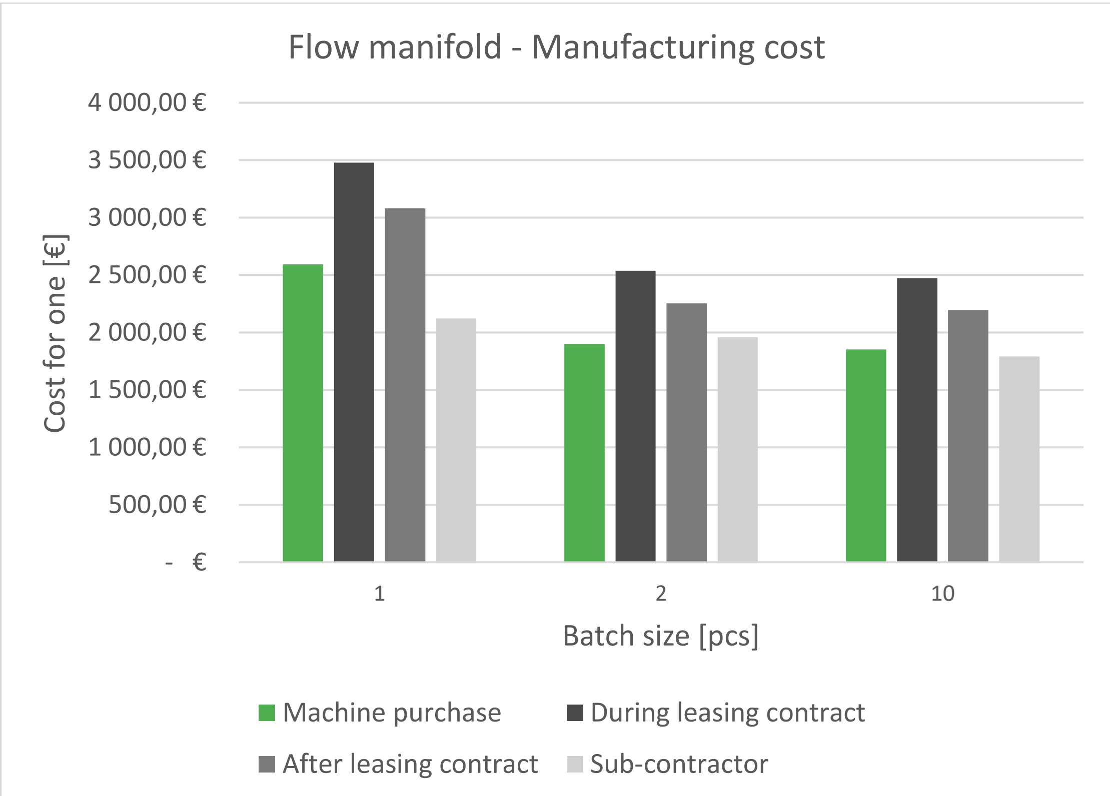

Figure 33. Manufacturing costs of flow manifold

Total lifetime costs were evaluated by using the two experimental study examples and producing only them with total productivity rate of 46 % (figure 34). The highest lifetime cost came from leasing contract scenario and the lowest from using sub-contractor. The result was surprising because the machine purchase scenario was assumed to be the cheapest solution in the long run.

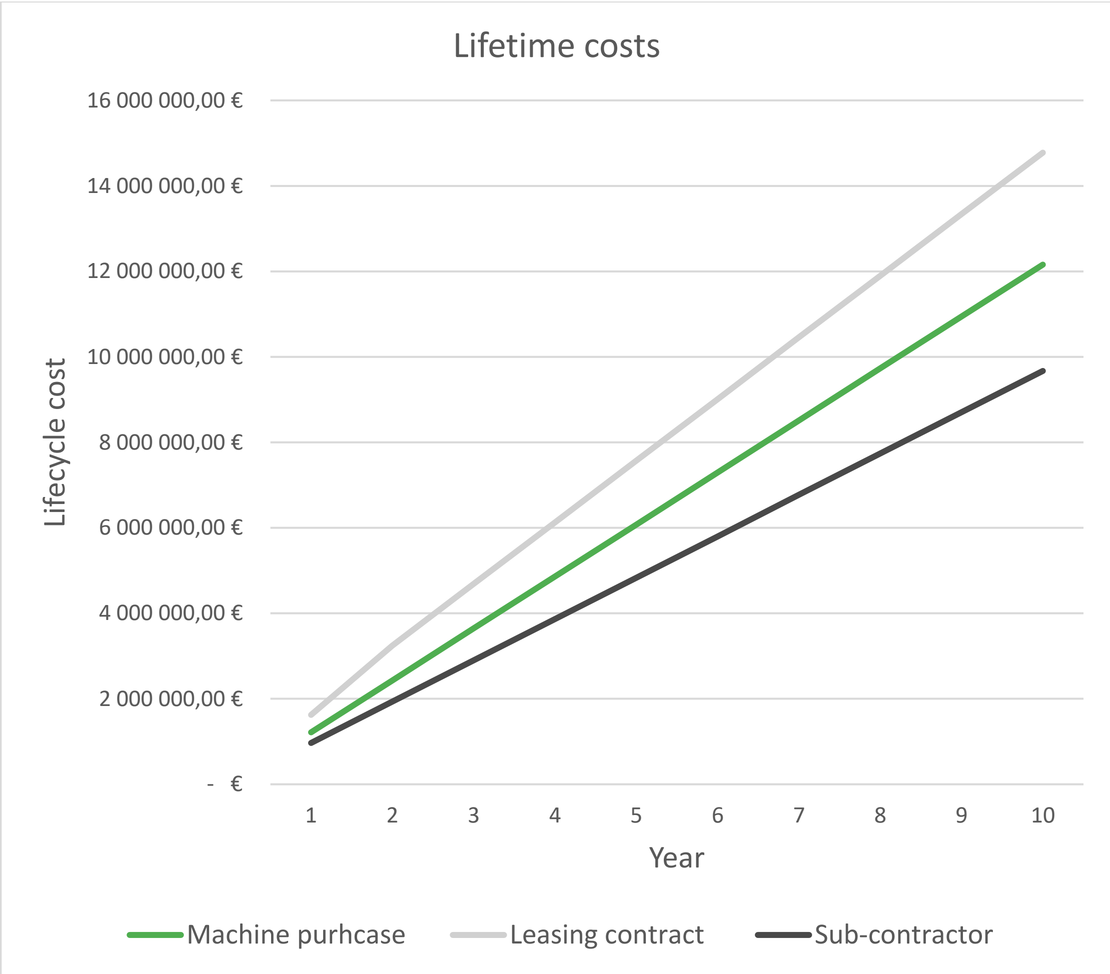

Figure 34. Total lifetime cost in three different scenarios

8.3 Factors to consider in DFAM

Factors to consider in designing differ highly from each other depending of the used technology. Additive manufacturing must be seen as an umbrella term for variety of different technologies. The same applies for conventional machining and therefore creating strict list of factors to consider would lead to unsatisfying result. In this work the DFAM factors were detected during experimental part through designing process which offered three approaching possibilities (figure 35). Two of them were mainly designing for reproduction which would lead to justified but not to the optimal solutions. Correspondingly, the redesigning process with “additive thinking” offer the most potential ground to produce added value.

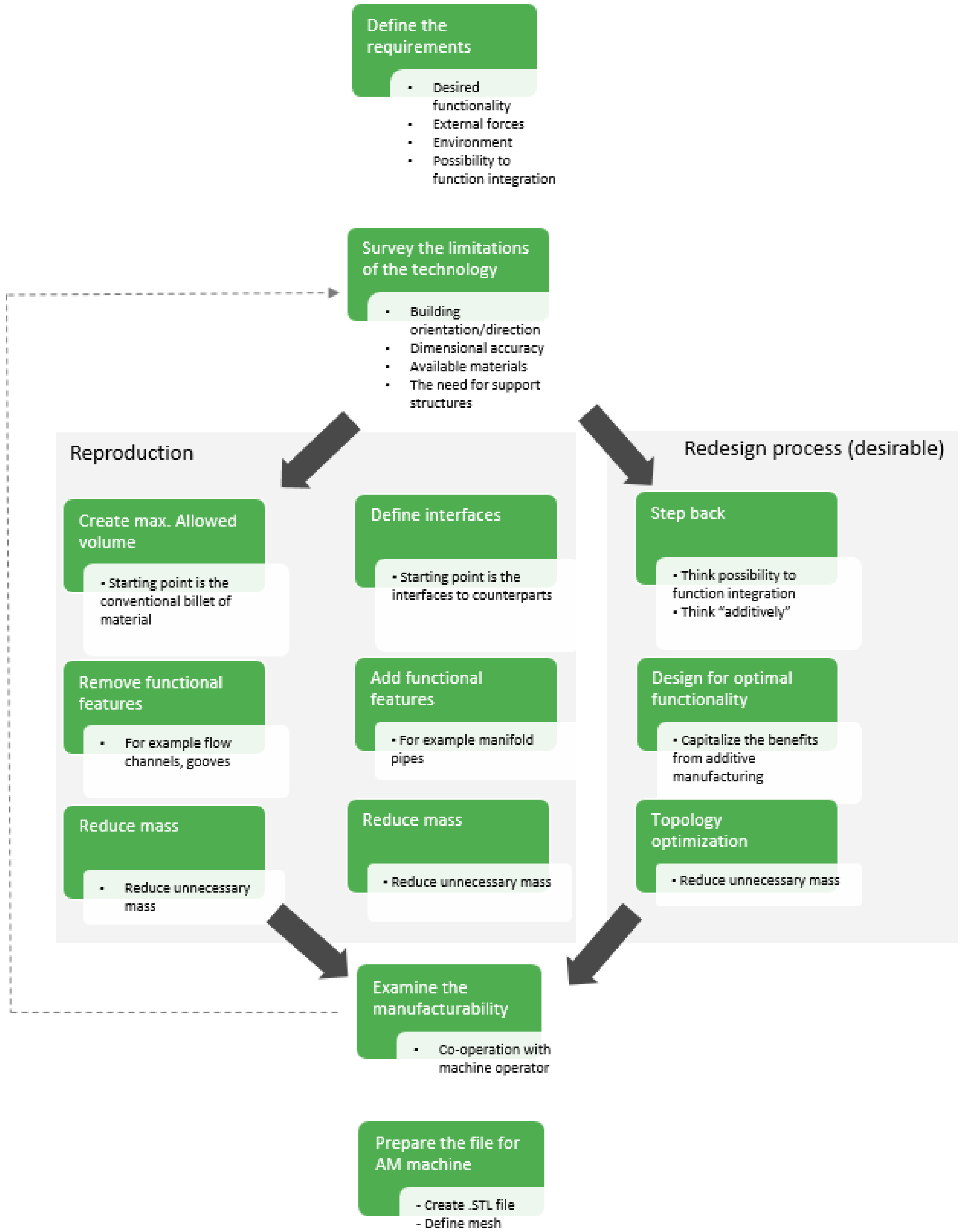

Figure 35. DFAM process chart with three different approaches

The process begins with defining the requirements. Then the used technology needs to be decided and designer must understand the possibilities and limitations of the considered technology. Depending on the case the designing can start from removing material from billet, defining the interfaces or stepping one step back from existing product. At the end the manufacturability needs to be examined with professionals in order to prevent additional costs. In this work the both experimental study cases were designed for powder bed fusion technology. The list below shows the factors that need attention:

- Overhanging
- Support structures
- Heat conduction
- Building orientation
- Building location
- Minimum gap thickness
- Volume of the part
- Attaching to building platform
- Movement of recoating arm
- Surface quality adequacy
- Powder removal

Depending on the case and used technology the list could look a lot different but it this work the succeeding of the experimental cases crystallized on the listed matters.

8.4 Conclusions

Additive manufacturing is a manufacturing method among others. It does not offer limitation free designing as is commonly expected. There are many limitations that need attention as there are with any other manufacturing method. The limitations are different from traditional methods which opens the possibility to manufacture the parts with AM that are not manufacturable with any other methods. This was proved with experimental parts which both were suitable for additive manufacturing.

To be most successful in application selection it should not be based only to existing parts and their improvement but instead to new applications that are designed for additive manufacturing from the very beginning. Thereby the whole system can be built to benefit from AM. At general state, the existing products that benefit to be light weight, are expensive to manufacture and are not optimal at current state are the best suited for consideration. Also, a possibility to reduce number of parts and shorten the manufacturing process are beneficial approaches but not sufficient alone.

As a result of this work it is not recommended to propose Valmet Rautpohja to invest in own metal additive manufacturing machine. There are many potential applications and two concepts were proven to be suitable, but the technology is still young and developing with very high speed. By investing to metal AM machine Valmet Rautpohja would be tied to a specified technological level for a long time. The learning process would probably take years before the investment begins to be profitable.

Still the metal AM technology is worthy of further investigations. More potential applications should be studied and the concepts tried out. Not only in Rautpohja but also in other locations of Valmet and also within different business lines. With this the needed volume of highly beneficial applications could be reached and a machine purchase could be aligned in co-operation with more stakeholders. The economic risk would be divided into smaller pieces and the knowledge could be centralized to one place that could be for example Sundsvall as they already have two years of experience.

As the manufacturing industry is going more in to additive technologies this thesis should be followed by a close co-operation with local AM sub-contractor 3D Formtech. This offers the opportunity to learn the possibilities, understand the limitations and investigate more applications without high economical risk. Additive manufacturing is not Valmet’s core competence but to keep up with the development the AM should be considered as highly competitive manufacturing alternative.

8.5 Further development proposal

By studying a couple of the potential proposed applications further the machine investment examination would be more justified due to higher loading of the AM machine. This thesis produced several items and ideas to study further to map the possibilities of AM from different point of views.

Additional entities to study further:

- Parts for pilot machines
- Small bearing housings
- Special tools
- Coatings for water removal elements with directed energy deposition technology
- Parts for hydraulic systems
- Last minute fix parts at pre-assembly
- Transportation subsidies

- Using additive manufacturing as a tool for production development

Parts designed in the experimental study should be designed in detail level, manufactured and tested in pilot machine. This would give the true understanding of the costs and functionality because in this work the purpose was only to prove the concept of AM. In a big organization the responsibility of development should be defined to guarantee the continuous developing so hiring an employee to lead the projects is proposed.

9 Discussion

The potential applications were sieved with an internet questionnaire and an evaluating chart. The other possible approach would have been data analysis of released parts using product data management system. This way the number of processed parts would have been significantly higher but new ideas would not have come out.

The manufacturing cost calculation processed only one technology and was based on rough estimations. The calculation did not take into account that sub-contractors would use the whole building capacity of the machines in every build so the manufacturing cost of producing only one part was significantly smaller. Still it can be used as guiding tool and template for further development.

At the beginning of the work the introductional presentations were held to different stakeholders. With the information from the presentations the personnel suggested different ideas for AM. The presentation was mainly based on SLM process because it was the most used technology. This could have affected participants to propose only applications which are suitable for that method. It might be that some of the achievable potential remained unused. Still many potential applications were found.

The reliability matters were included in early step and the whole work was planned in frames of reliability. The participants presented the target group well. During the last week of surveying potential applications, the same ideas started to appear again. This saturation tells that most of the ideas were found. The internet questionnaire was not the only source of information but observation and interviewing were used so triangulation was implemented. The study could be repeated and the results would be similar because of the systematic process. The results were discussed with supervisors and no dissenting opinions were told. Still some degrees of freedom were included. For example, in the evaluating of the ideas not all the criteria were based on theoretical background. To improve the reliability of the study the idea screening process could have been repeated with another target group but this was impossible because of limited timeframe. As a conclusion the results of the study are considered reliable but not fully generalizable as such. The further decisions and conclusions regarding the results were made by Valmet after finalizing this thesis so they could not be included to this work.

Given goals were achieved in the study. Also, the research questions were answered and further development proposals were made. Valmet received new information, a list of potential applications, a calculation tool to evaluate the manufacturing costs, innovative new designs and connections to AM service suppliers. At the same time the awareness level of the AM possibilities and limitations were increased among Valmet's personnel and two concepts were proven with experimental study.

Thanks to the survey responders, professionals from the industry and participants who made this thesis possible. Thanks to Henrik Traff for hosting the visit in Sundsvall. Special thanks to Supervisors Sampo Immonen, Juha T. Mäkinen, Jukka T. Heikkinen and Juha Ehrola.

References

Advantages of Wire AM vs. Powder AM. N.d. Text at company's website. Referred 6.2.2018. http://www.sciaky.com/additive-manufacturing/wire-am-vs-powder-am.

Alonen, A. Hietikko, E. Hoffren, M. Kesonen, M. Urpilainen, A. 2015. Kokemuksia metallikappaleiden ainetta lisäävästä valmistuksesta. DEADMAN – Tutkimushankkeen loppuraportti. Savonia-ammattikorkeakoulu. DeadMan - tutkimushanke.

Brandl, E. Heckenberger, U. Holzinger, V. Buchbinder, D. 2011. Additive manufactured AlSi10Mg samples using Selective Laser Melting (SLM): Microstructure, high cycle fatigue, and fracture behavior.

Siebert, M. N.d. Breakthrough with 3D printed Gas Turbine Blades. Article in Siemens' website. Referred. 24.1.2018. https://www.siemens.com/innovation/en/home/pictures-of-the-future/industry-and-automation/additive-manufacturing-3d-printed-gas-turbine-blades.html

Castells, R. 2016. DMLS vs SLM 3D Printing for Metal Manufacturing. Article in Element website. Referred 25.1.2018. https://www.element.com/nucleus/2016/06/29/dmls-vs-slm-3d-printing-for-metal-manufacturing.

Direct Metal Laser Sintering. N.d. Article in Custompart website. Referred 24.1.2018. http://www.custompartnet.com/wu/direct-metal-laser-sintering.

Gibson, I. Rosen, D. Stucker, B. 2014. Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. Springer. New York.

Groundbreaking NanoParticle Technology. N.d. Info text from machine builder website. Referred 26.1.2018. http://xjet3d.com/technology-new/.

Heikkinen, T. 2018. CEO of AMFinland. Email conversation 20.2.2018. Receiver J. Kuikka. Answers to questions regarding current state of additive manufacturing.

Henrik, T. 2018. Additive design engineer at Valmet Sundsvall. Email conversation 14.2.2018. Answers to questions regarding the use of metal additive manufacturing at Sundsvall.

High Level Processes: Material Jetting. 2017. Blog post in Bintoa website. https://www.bintoa.com/material-jetting/. Referred 26.1.2018.

Hopkins, N. Dickens, P. 2003. Analysis of rapid manufacturing-using layer manufacturing processes for production. Journal article. Journal of Mechanical Engineering Science 217. 31-39. Professional Engineering Publishing.

Hornick, J. Bhushan, A. 2016. More 3D Printing Patents Are Expiring Soon: Here's a Roundup. News in a 3DPrintingIndustry website. Referred 26.1.2018. https://3dprintingindustry.com/news/more-3d-printing-patents-are-expiring-soon-heres-a-roundup-96561/.

Hybrid multi-tasking machine-AM. N.d. A text at Mazak website. Referred 26.4.2018. https://www.mazakeu.com/machines-technology/technology/hybrid-multi-tasking-machine/

Isoaho, T. 2018. Tigate sales representive. Email conversation 9.5.2018. Receiver J. Kuikka. Answers to questions regarding possible coating solutions.

ISO/ASTM 52900:2015. Additive manufacturing. General principles. Terminology. Referred 25.1.2018.

Kananen, J. 2017. Kehittämistutkimus interventiotutkimuksen muotona.

Kananen, J. 2012. Kehittämistutkimus opinnäytetyönä. Kehittämistutkimuksen kirjoittamisen käytännön opas.

Kananen, V. 2018. CEO of 3Dstep. Email conversation 19.2.2018. Receiver J. Kuikka. Answers to questions regarding current state of additive manufacturing.

Laakko, L. Linnamäki, I. 2017. Perälaatikon reunasyöttömoduulin kehittäminen. Machine design project. University of Oulu.

Laine, P. Saarinen, K. 2018. Financial statement 2017. Referred 6.3.2018. https://www.valmet.com/globalassets/investors/reports--presentations/interim-reviews/2017/presentaatio-tilinpaatostiedote-2017.pdf

Lasertec 65 3D hybrid. N.d. A text at DMG Mori website. Referred 26.4.2018. https://us.dmgmori.com/products/machines/advanced-technology/additive-manufacturing/powder-nozzle/lasertec-65-3d-hybrid

Lefky, C. Zucker, B. Wright, D. Nassar, A. Simpson, T. Hildreth, O. 2017. Dissolvable Supports in Powder Bed Fusion-Printed Stainless Steel. Article. Referred 5.2.2018. http://online.liebertpub.com/doi/pdf/10.1089/3dp.2016.0043

Lindeman, C. Jahnke, U. Reiher, T. Koch, R. 2014. Towards a sustainable and economic selection of part candidates for Additive Manufacturing. Rapid prototyping Journal. Referred 20.2.2018.

Lumex Avance-60. N.d. A text at company website. Referred 3.5.2018. http://www.lumex-matsuura.com/english/contents/lumex60.html

Metal powder alloys. N.d. A text at company website. Referred 13.2.2018. https://www.materials.sandvik/en/products/metal-powder/list-of-materials/

Metal powders for AM. N.d. A text at Renishaw website. Referred 7.2.2018. http://www.renishaw.com/en/metal-powders-for-am--31457

Metal 3D printing: Technology of the future for lighter and more compact engines. 2017. Press release. Renaults truck deliver. Referred 12.2.2018. http://corporate.renault-trucks.com/en/press-releases/2017-01-11-metal-3d-printing-technology-of-the-future-for-lighter-and-more-compact-engines.html

Murray, K. 2018. Sales and Marketing Manager at Sandvik Osprey Ltd. Email conversation 14.2.2018. Receiver J. Kuikka.

Nonabrasive Cleaning. N.d. Information at company's website. Referred 31.1.2018 http://www.iepco.ch/en/technologies/nonabrasive-cleaning

Nyrhilä, O. Kotila, J. Lind J-E. Syvänen, T. N.d. Industrial Use of Direct Metal Laser Sintering. Report from Electrolux.

Ohnsman, A. 2017. Divergent 3D raises over $65 million for its car factory of the future. Press release. Referred 12.2.2018. https://www.forbes.com/sites/alanohnsman/2017/11/21/divergent-3d-raises-over-65-million-for-its-car-factory-of-the-future/#64f4b8b050fc

Pricing. 2017. Pricing information of the manufacturer. Referred 1.2.2018. https://www.desktopmetal.com/assets/uploads/DM-0018-EU-Studio-System-Price-Sheet-v2.1.pdf

Redwood, B. N.d. Additive Manufacturing Technologies: An Overview. Article in 3dhubs website. Referred 25.1.2018. https://www.3dhubs.com/knowledge-base/additive-manufacturing-technologies-overview#powder-bed-fusion.

Riemer, A. Leuders, S. Thöne, M. Richard, H.A, Tröster, T. Niendorf, T. 2013. On the fatigue crack growth behavior in 316L stainless steel manufactured by selective laser melting. Article. Referred 2.2.2018. https://www.sciencedirect.com/science/article/pii/S0013794414000757

Ruffo, M. Tuck, C. Hague, R.J.M. 2006. Cost estimation for rapid manufacturing – laser sintering production for low to medium volumes. Journal article. Journal of Engineering Manufacture.

Ruokolainen, T. 2018. Sales and development representive at Alu-Releco Ltd. Email conversation 9.4.2018. Receiver J. Kuikka.

Southway, N. 2017. The Design Rules of AM Metal Technology. Article. Referred 8.2.2018. https://www.design-engineering.com/guides/amt-1004026987/.

Studio System. N.d. Manufacturer system overview. Referred 1.2.2018. https://s3.amazonaws.com/desktopmetal/DM-0008-US-Studio-System-Overview-v1.4.pdf

The EBAM 300 System. N.d. Info in companys website. Referred 6.2.2018. http://www.sciaky.com/additive-manufacturing/metal-additive-manufacturing-systems

Traff, H. 2018. Sundsvall AM information. Email 14.2.2018. Receiver J. Kuikka. Information of additive manufacturing for thesis worker.

Vaajoki, A. 2017. Post-processing of AM specimens. Educational material. Technical Research Centre of Finland.

Vaajoki, A & Metsä-Kortelainen, S. 2016. AM-prosessin integrointi tuotantoon – metalliosien valmistuksen työvaiheet. Study report. VTT-R-03327-16.

Valmet general presentation. 2017. General presentation at Valmet website. Referred 6.2.2018. https://valmetsites.secure.force.com/solutionfinderweb/FilePreview?id=06958000001ARK8AAO&_ga=2.61428328.577502545.1517907335-1809945074.1516954970.

Varotis, A. N.d. Introduction to Binder Jetting 3D printing. Article in 3dhubs website. Referred 25.1.2018. https://www.3dhubs.com/knowledge-base/introduction-binder-jetting-3d-printing.

Vihinen, J. 2018. Email 14.3.2018. Receiver J. Kuikka. Information regarding Direct Energy Deposition machine of Tampere University of Technology.

World Paper Markets up to 2030. 2014. Pöyrys paper market insights through 2030.

Zistl, S. N.d. 3D Printing: Facts & Forecasts. Forecast from Siemens. Referred 2.3.2018. https://www.siemens.com/innovation/en/home/pictures-of-the-future/industry-and-automation/Additive-manufacturing-facts-and-forecasts.html

Appendices

Appendix 1. The internet questionnaire used to idea screening process

Survey of potential use of metal 3D printing

Welcome to the questionnaire!

Answering takes approximately 10-15 minutes.

Please answer in Finnish or in English.

Answer honestly and according to your own feelings.

Introductory presentation was held about a week ago to your group.

Please do not hesitate to add any ideas that comes to your mind.

Please focus on parts that weight less than 30 kg.

Feel free to send attachments (eq. drawings, pdf-files etc.) to email addres below:
jasperi.kuikka@valmet.com

1. Contact information is used only to deliver the awards *

First name

Last name

Email

2. I have expertise in following:
(Select many if necessary)

- Design engineer
- Process specialist/manager
- Development engineer/manager
- Manufacturing specialist
- Product manager
- Concept manager
- Other, describe:

3. Group *

- PAP_PM_Tech_Former&Press&LineDesign
- PAP_PM_Tech_Dryer&Air
- PAP_PM_Tech_Headbox
- PAP_PM_ENG_WetEnd
- PAP_PM_Tech_Rolls&Components
- Other, describe:

4. Preliminary expectations:

1. Not at all
2. Probably no
3. I don't know
4. Possibly yes
5. Definately

Do you consider that metal 3D printing ... *

	1	2	3	4	5
...offer new possibilities to your own work?	○	○	○	○	○
...can help to improve the functionality of parts/assemblies?	○	○	○	○	○
...offer help to improve competitiveness?	○	○	○	○	○
...can be used as end-use production?	○	○	○	○	○
...possibilities should be studied in Valmet (PAP)?	○	○	○	○	○
...will become common option within normal manufacturing methods?	○	○	○	○	○

5. Have you recently worked with parts/assemblies with following attributes?

Consider parts/assemblies that are smaller than 400 x 400 x 400 mm.

1. No
2. I don't know
3. Yes
*

	1	2	3
The geometry of the part is complicated	☐	☐	☐
More complicated geometry would improve the functionality	☐	☐	☐
Low weight is an advantage	☐	☐	☐
Manufacturing with traditional methods is complicated	☐	☐	☐
Manufacturing with traditional methods is expensive	☐	☐	☐
Part is specially tailored for one project	☐	☐	☐
Part is essential for functionality of the main product	☐	☐	☐
Has a complex internal geometry	☐	☐	☐

List parts/asseblies to fields below that might be potential to manufacture by metal 3D printing. Do not hesitate to add parts that need to withstand special requirements (eg. surface roughness, hardness or strength)

Add drawing number, name of Catia V6 model or other annex IF such are available

6. Geometrically challenging parts:

7. Parts that benefit to be light weight:

8. Parts that are challenging to manufacture with traditional methods:

9. Parts that you believe/know to be unreasonable expensive to manufacture:

10. Parts that are tailored for each project:

11. Expensive to manufacture and manufacturing quantities are low:

12. Has complex internal geometry:

13. Describe other possible uses/parts to be manufactured by metal 3D printing:

Appendix 2. Results from internet questionnaire

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Appendix 3. Idea evaluation criterias and results

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Appendix 4. Cost evaluation tool

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Appendix 5. Requirements list for Tail blower

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Appendix 6. Requirements list for flow manifold

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Appendix 7. The first desing of flow manifold

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Appendix 8. Final desing of the flow manifold

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Appendix 9. Flow manifold simulation results

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Appendix 10. Nozzle-manifold pipe self-locking geometry

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Appendix 11. Tail blower simulation results

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