BUSINESS
FINLAND

ADDITIVE MANUFACTURING CENTER OF EXCELLENCE (AMCE) IN FINLAND

FEASABILITY STUDY

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Appendicies

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SYMBOLS AND ABBREVIATIONS

AM	Additive manufacturing
AMCE	Additive manufacturing center of excellence
BJ	Binder jetting
CAD	Computer-aided design
CAPEX	Capital expenditure
CFD	Computational fluid dynamics
COGS	Cost of goods sold
CT	Computed tomography
DED	Directed energy deposition
DMD	Direct metal deposition
DMLS	Direct metal laser sintering
EBM	Electron beam melting
EDM	Electrical discharge machining
ET	Electromagnetic testing
FDF	Finnish defense forces
FEM	Finite element method
HIP	Hot isostatic pressing
LPBF	Laser powder bed fusion
MBJ	Metal binder jetting
MJ	Material jetting
MTBF	Mean time between failures
NDE	Nondestructive evaluation
NDT	Nondestructive testing
NCR	Non conformances
OPEX	Operational expenditure
PED	Pressure equipment directive
PT	Liquid penetrant testing
RCA	Root cause analysis
SLM	Selective laser melting
UT	Ultrasonic testing

1 INTRODUCTION

Finland will replace its Hornet fighters in 2021, and the bidding process for the program is now ongoing. The procurement includes an obligation for industrial participation: the winning bidder and its partners will cooperate with Finnish companies, with the value of the participation being 30 percent of the purchase price (Business Finland, 2019).

The primary objective of industrial participation is to ensure the military security of supply of defense industry products from Finnish and foreign manufacturers and the availability of critical technology in any circumstances. The secondary objective is to ensure the development of Finnish technology and competence in the future as well.

Industrial participation (IP), involves an evaluation of how cooperation between HX tenderers and domestic industry would be realized. The total value of the participation is approximately EUR 2-3 billion.

Additive manufacturing (AM) has passed the peak of the hype curve, and is steadily becoming an established manufacturing methodology. It is deemed critical that qualification of components aimed at serial production is ramped up in order to not fore go opportunities that will be realized abroad, for example in Sweden or Germany.

Finnish defense forces have listed additive manufacturing as one of the interest areas in industrial cooperation. (Indirect IP).

Currently, there are no AM service bureaus with needed equipment and competence to provide manufacturing services for critical additive manufacturing applications in Finland. Finland is also missing an innovation center similar to AMEXI in Sweden.

This is a unique opportunity to create industrial-scale additive manufacturing expertise in Finland, which serves and develops Finnish defense and security industry expertise, and also brings technical expertise to the use for other industries.

The rise of AM to being one of the most interesting technological trends has been noted in the highest levels of Finland as well – in the parliament. AM has been noted in the parliament's Committee for the Futures report titled *A hundred new possibilities 2018-2037*. One of the observations made for AM is the need for new professions and skills; 3D printer operator, biomimicry designer, raw material consultant and 3D modeler were some of the many noted skills and professions needed in the future (Linturi & Kuusi, 2018).

This feasibility study will support the decision making in Finland and HX tenderers, and gives estimations of the investments needed for AM serial production.

1.1 Metal AM in brief

There are seven categories of additive manufacturing technologies recognized in ISO/ASTM 52900:2015(E), three of the most popular will be described in more detail for creation of metal components and are included in the process schematics of Figure 1.

Powder bed fusion can be described as an AM process whereby thermal energy selectively fuses metal particles in a powder bed. The thermal energy is produced by laser (a.k.a. laser powder bed fusion (LPBF), selective laser melting (SLM), direct metal laser sintering (DMLS), etc.) or electron beam (a.k.a. electron beam melting (EBM)). Manufacturers of these machines include EOS, 3D Systems, Renishaw, SLM Solutions, Additive Industries, Concept Laser, Xact Metal, AddUp, DMG Mori, Aurora Labs, Velo3D, Farsoon Technologies, and Arcam.

Binder jetting is an AM process in which a liquid bonding agent is selectively deposited to bind powder particles. In the case of metal binder jetting (MBJ), the metal powder is bound to produce a so-called green part. The green part needs to be sintered to remove the binder and create a full-metal end component. Manufacturers of machines for metal binder jetting include Desktop Metal, Digital Metal, ExOne, 3DEO, XJet, and HP.

Directed energy deposition (DED) is an AM process which uses a thermal energy source to melt and thereby fuse materials as they are being deposited. The thermal energy source can be produced with a laser, electron beam, plasma arc, or gas metal arc, and the feedstock can come in the form of powder or wires . Manufacturers of these systems include Trumpf, BeAM, Optomec, InssTek, DigitalAlloys, Gefertec, Norsk Titanium, DMG Mori, Lincoln Electric, Mazak, FormAlloy, and Sciaky.

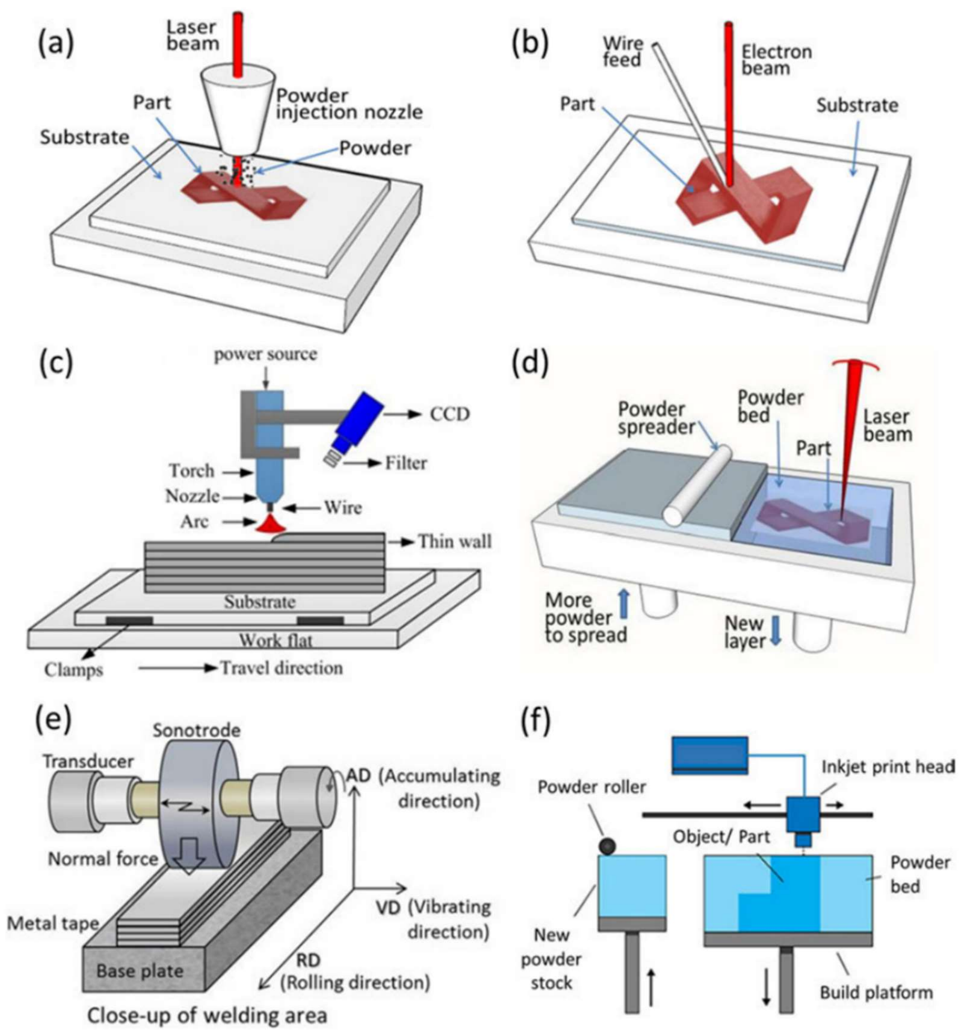


Figure 1. Schematic diagram of (a) DED with powder feed and laser, (b) DED with wire feed and electron beam, (c) DED with wire feed and gas metal arc, (d) LPBF, (e) ultrasonic AM process, (f) binder jet process (DebRoy, et al., 2018)

None of these AM technologies is optimal or even feasible for all applications. Across the technologies there is variation in materials available, achievable mechanical properties, as-built surface finish, required post processing, available build volume, etc. Figure 2 gives insight on how these technologies compare in terms of costs, lot size and part performance.

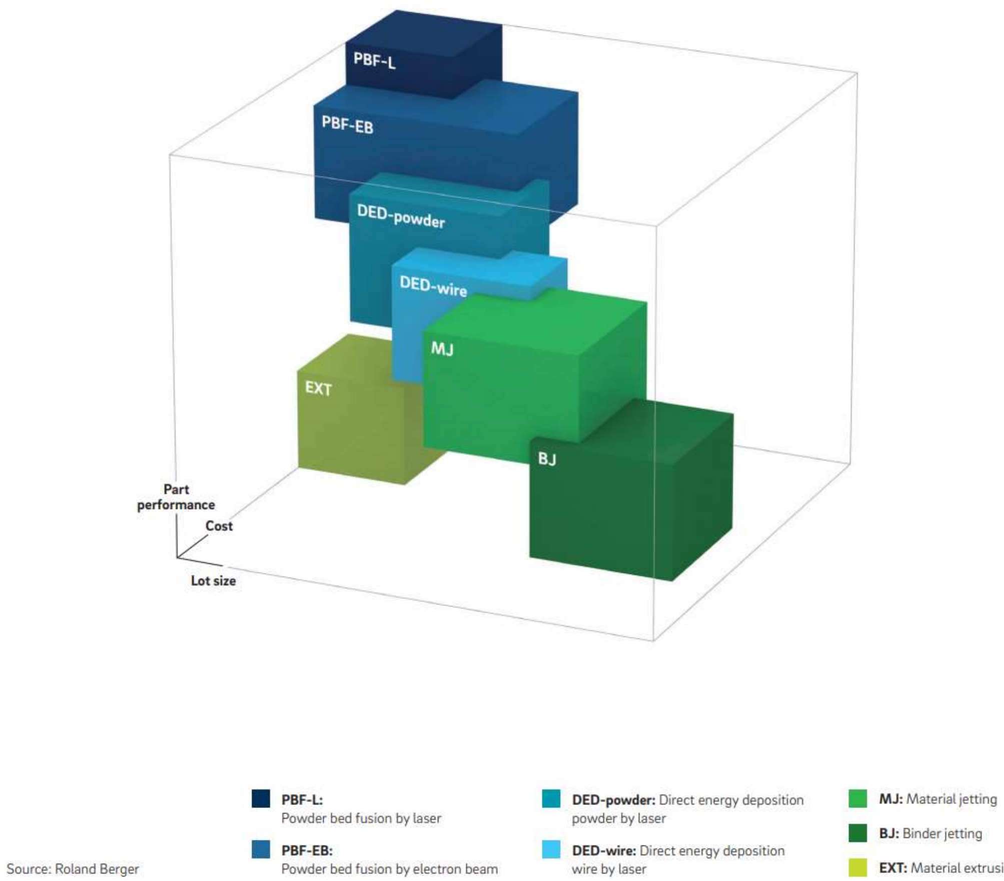


Figure 2. Comparison of metal AM technologies by performance, cost, and lot size (Roland Berger, 2018).

1.2 Requirements for metal AM production of qualified critical component

In order to better understand the state of AM in Finland and the key factors inhibiting growth and uptake of AM technologies for critical components, it is good to first have an overview of the path traversed to go from initial concept to qualified component. Figure 3 describes the steps needed for a typical LPBF part, as this is the AM technology that this section will primarily focus on. These steps can be broken into five general categories: design, build preparation, manufacturing, post processing and certification. In order to complete the necessary steps to produce the qualified component, there is a requirement to have access to needed information, equipment, software tools and trained individuals.

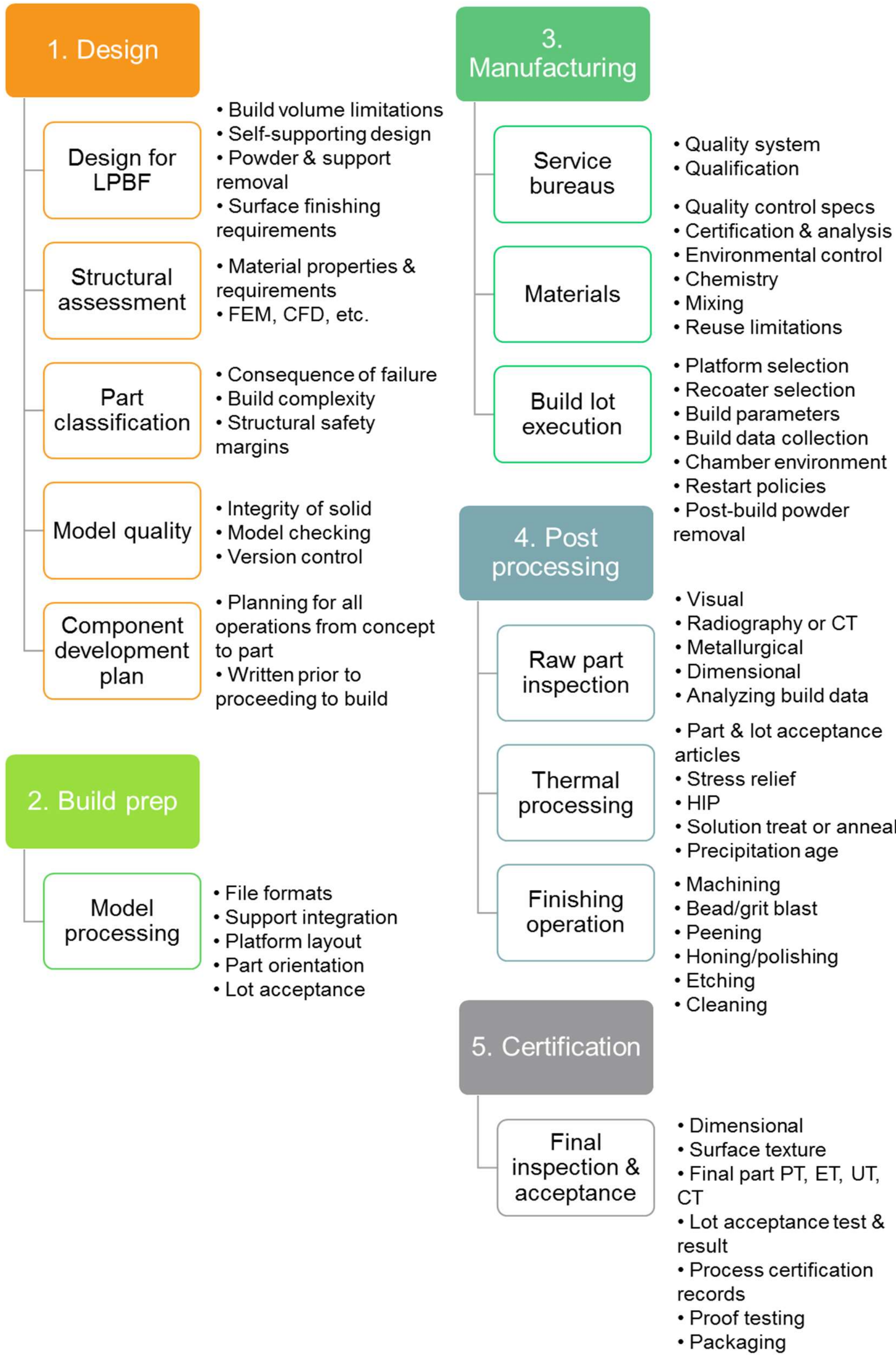


Figure 3. Necessary steps in creation of a qualified component created by LPBF; based on (Wells, 2018).

1.2.1 Design

Design for metal additive manufacturing requires an understanding of the geometric freedoms and limitations provided by the manufacturing method, as well as the effect of choices made with regard to the manufacturing and post-processing of the component on its final performance characteristics. The designer will naturally need to keep in mind factors such as build volume limitations, self-supporting features, powder and support removal, and surface finishing requirements.

Skilled engineers and adequate software tools are needed for 3D modelling of potentially very complicated structures (e.g. bionic design, lattice structures, conformal channels, etc.). Advanced simulation techniques should be utilized to optimize material use (e.g. generative design, topology optimization), predict performance and life span of the component (e.g. FEM, CFD) and simulate the effects of the manufacturing process.

Material properties for typical printed and post-processed (thermal and surface treatments) parts need to be well-defined upfront so performance and lifetime of critical components can be predicted during the design process. Limited information is available from AM machine and powder providers on the material properties of printed metal components, but key information is often missing due to the large number of variables effecting the properties of the AM end-component. These include:

- Location and orientation of component on build platform during printing
- Powder characteristics (e.g. chemical composition, particle size distribution, morphology, flowability, etc.)
- Process parameters (e.g. laser power, scan speed, layer thickness, hatch definition, etc.)
- Thermal post-processing (e.g. stress relief, HIP, solution treatment, anneal, precipitation aging, etc.)
- Surface finishing operations (e.g. machining, sand blasting, etc.)

All of the variables listed above have a direct effect on the fatigue and fracture characterization of AM materials (Seifi, et al., 2017).

After a structural assessment of a potential AM design is performed, there are still several steps to be taken before preparing for the actual build. These include classification of the part based on complexity, consequences of failure and safety margins, checking the quality of the 3D model that will be utilized in the print job, production of necessary 2D drawings for use in the manufacturing process, and creation of a component development plan that describes all operations from concept creation through part acceptance.

1.2.2 Build preparation

Build preparation begins with import of 3D CAD model data for each component printed in single build job into the build machinery software. Some potential for problems can arise here depending on format of the CAD model, accuracy of the translation of the 3D model with respect to critical features, and the impact of software updates on the translation of legacy parts.

The build layout must then be created, with each component positioned and oriented relative to the build platform, with necessary support structures created. The orientation of the parts, which should be considered already during the design phase, is of particular importance as it plays a key role in determining both quality and cost of the build. The orientation affects build time, the volume and location of needed support structures, surface roughness, residual stresses, and distortion levels.

Qualification of the manufacturing procedure needs to be considered at this stage to ensure that the three primary aspects related to quality assurance are upheld:

- Technical requirements: the additive manufactured part meets the technical requirements for this type of component
- Repeatability: the result is repeatable across different batches/orders
- Traceability: the complete history of the component is known - from concept, through raw material, to final product (DNV GL AS, 2017)

To assist with this and quality assurance of the end component, each build layout will likely include additional pieces for destructive testing. Example test articles may include density cubes and specimen for tensile, fatigue, and Charpy V-notch impact tests.

1.2.3 Manufacturing

The key tasks in the actual manufacturing of the component by LPBF are related to the metal powder used in the build, the chosen machine, and the execution of build itself. They are described in more detail below.

Qualification of critical components by LPBF will require equipment and know-how related to the selection, handling, analysis, and recycling of the metal powder. The final quality of additively manufactured components are influenced significantly by characteristics of the feedstock materials (DebRoy, et al., 2018), thus the metal powder used needs to meet certain specifications in order to guarantee that printed parts perform as expected. Feedstock should be characterized to specify material chemistry, particle size range and distribution, morphology, flow rate, and oxygen content (Lloyd's Register Group Ltd; TWI Ltd., 2017). This information is needed for every powder batch, whether virgin powder directly from the vendor, recycled powder, or a mix of the two. Power production and handling is also key as oxygen and hydrogen content of the powder can have a significant influence on the final material properties of an AM component (Dietrich, Wunderer, Huissel, & Zaeh, 2016).

It goes without saying that the choice of printer, metal powder, and process parameters will significantly impact the resulting quality of the printed part. High density parts with optimal surface quality and minimal defects are required to achieve satisfactory mechanical strength and fatigue characteristics. Process parameters such as powder layer thickness, laser power, laser spot size, laser scan speed, hatch distance, laser path/strategy combined with the metal powder properties, build environment controls (e.g. inert gas, platform preheating) and the position and orientation of the component on the build plate will dictate the resulting process signature of the build component. These factors in turn determine the geometric accuracy, metal properties including grain size and morphology, surface roughness, internal defects, and residual stresses of the component.

1.2.4 Post-processing

An additive manufactured component is by no means finished when the last layer has been printed. After the parts and build plate have cooled (in LPBF), the excess powder needs to be removed from the build volume for sieving and recycling. An initial inspection of the raw or as-built version of the components should be performed that includes at a minimum a visual and dimensional inspection of the parts as well as analysis of collected build data.

Next, the entire build platform with all parts attached will undergo a stress relief cycle. This is necessary to relieve potentially high internal stresses generated during the build process that might cause significant warpage or cracking if not addressed before the part is removed from the build plate.

After stress relief, all of the parts can be removed from the build platform. This is typically done with wire EDM or bandsaw. After removal each individual part can receive further thermal treatments such as HIP, solution treatment, annealing, and precipitation aging as needed. The thermal treatments applied can significantly affect the material properties of the end component, and thus should be chosen carefully depending on the use case and considered already during the design phase. Most currently used heat treatment regimes are based on standards that were not created for AM metals, and thus for e.g. with fatigue-critical components they might not be optimal for achieving the best possible performance.

When all of the thermal post-processing is completed, the finishing operations will begin. These are conducted in order to remove support structures and achieve the required surface finish and dimensional accuracy required. Typical processes include machining, bead or grit blasting, peening, polishing and etching.

1.2.5 Inspection and testing

As indicated in the previous sections, quality assurance for AM is not performed in a single step, but rather requires a well-planned series of inspections, measurements and analyses which are documented throughout the entire workflow. The selected inspection and testing routine must consider component criticality as well as the possible impact arising from some lack of repeatability due to the complexity and large number of influencing factors of the AM process. The component classification specified during the design phase dictates the needed quality level, and thus the critical defect size and therefore which non-destructive testing methods are suitable for inspection (Lloyd's Register Group Ltd; TWI Ltd., 2017). A number of non-destructive testing methods that are potentially suitable for printed metal components are listed in Table 1, along with the type of defects that these tests can measure or identify.

In addition, metallography, mechanical testing, chemical analysis, and other destructive tests (as in Figure 4) may be required of test specimen or samples of the final product, especially when ramping up production. It is also common, when production approaches mass manufacturing, that test specimen from the build job will be stored for traceability and possible future needs, e.g. if an error or fault in the manufacturing is detected.

One existing challenge related to the inspection and testing of metal AM is that standards to help support qualification and certification of components are still under development (Seifi, et al., 2017).

Table 1. Summary of non-destructive testing (NDT) methods for AM; modified from (ASTM, 2014).

Defect Class	CT/RT/CR/DR	ET	METB	PCRT	PT	TT	UT	AE	LT	ND	MT	VT
Surface	X^{C}	X^{D}	X	…	X^{D}	…	…	…	…	…	…	X
Porosity	X	X^{D}	…	X	X^{D}	…	X	…	…	…	…	X^{E}
Cracking	X	X^{D}	…	X	X^{D}	X	X	X	X^{F}	…	X	X
Lack of Fusion	X	X^{D}	…	X	X^{D}	X	X	X	…	…	X	…
Part Dimensions	X	…	X	…	…	…	…	…	…	X^{G}	…	…
Density[H]	X^{I}	…	…	X	…	…	…	…	…	…	…	…
Inclusions	X^{J}	X^{D}	…	X	…	X	X	…	…	…	…	…
Discoloration	…	…	…	…	…	…	…	…	…	…	…	X
Residual Stress	…	$X^{D,K}$	X	X	…	…	…	…	…	X	…	…
Hermetic Sealing	…	…	…	…	…	…	…	…	X^{F}	…	…	…

[A] Abbreviations used: … = not applicable, AE = acoustic emission, CR = computed radiology, CT = computed tomography, DR = digital radiology, ET = eddy current testing, LT = leak testing, MET = metrology, MT = magnetic particle testing, ND = neutron diffraction, PCRT = process compensated resonance testing, PT = penetrant testing, RT = radiographic testing, TT = thermographic testing, UT = ultrasonic testing, VT = visual testing

[B] Includes digital imaging

[C] Especially helpful when characterizing internal passageways or cavities, or other internal features not accessible to MET, PT or VT

[D] Applicable if on surface

[E] Macroscopic cracks only

[F] If large enough to cause a leak or pressure drop across the part

[G] Conventional neutron radiography (NR) allows determination of internal and external dimensions

[H] Pycnometry (Archimeded principle)

[I] Density variations will only show up on imaged regions having equivalent thickness

[J] If inclusions are large enough and sufficient scattering contrast exists

[K] Residual stress can be assessed if resulting from surface post-processing (e.g. peening)

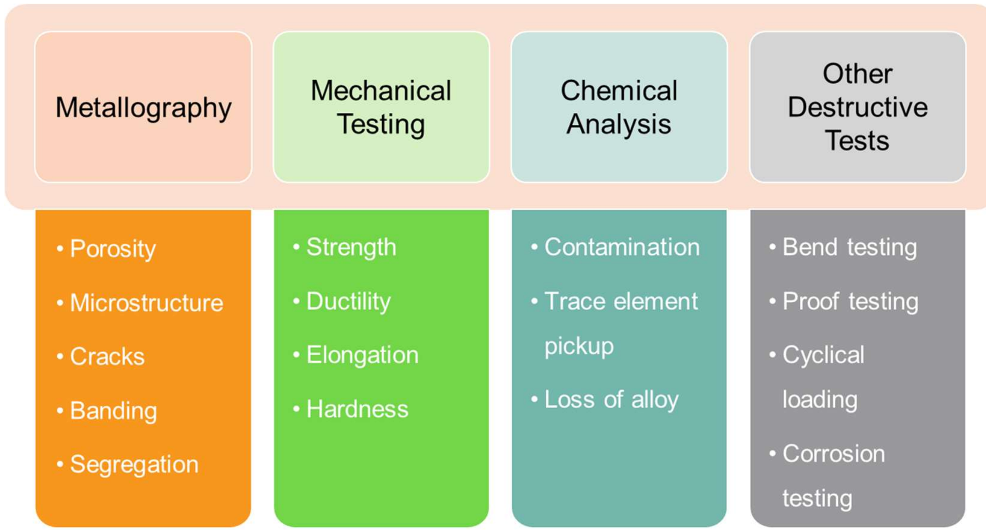


Figure 4. Summary of destructive testing methods for metal AM, modified from (Milewski, 2017).

1.3 Quality levels in metal AM

Every additively manufactured component has its own requirements in terms of needed performance level and acceptable manufacturing costs. Therefore it is important to understand these requirements upfront so that the part can be manufactured to a suitable quality level. The quality of metal AM can be divided into five levels as seen in *Figure 5*, with each described in more detail below. Moving up a level within the pyramid adds to the requirements for every stage of the process, from design through manufacturing, post-processing and testing and inspection, and therefore the skill level and resources required in every stage increases as well.

Level 1 – Part needs to be made out of metal

In many cases there is no need to create metal components having superior mechanical properties, it is enough that the components are simply metal and no other performance requirements exist.

Level 2 – Data sheet values should be met

In most cases at least data sheet values should be met for metal components. This means that when designing e.g. load-bearing components we can trust that the service bureau creating the component produces a part with material properties that meet or exceed data sheet values. In metal AM, the final material properties are created by a combination of the manufacturing process and heat treatments after the build.

Level 3 – Critical component with dynamic loads

Dynamic loads introduce a phenomenon called fatigue which occurs in structures, resulting in localized structural damage and the growth of cracks. Standard material data sheets available from machine providers do not include fatigue data, and publicly available fatigue data is very limited. Big players in AM like aerospace companies have done their own tests to acquire sufficient fatigue data of printed components to use in design.

Level 4 –Critical component – classification needed (PED / oil & gas / etc.)

When a part has an extremely critical role it is needed to certify the materials production where AM is being used as a manufacturing method. Such is the case when manufacturing components going under Pressure Equipment Directive (PED) for instance.

Level 5 – Extremely critical components to aerospace, nuclear plants, etc.

The highest level of quality is required when creating critical components for aerospace or nuclear energy sector. These components require certification e.g. for manufacturing, for the components themselves, and they need to go under rigorous testing. This is by far the heaviest process an AM component needs to go through to get acceptance for use.

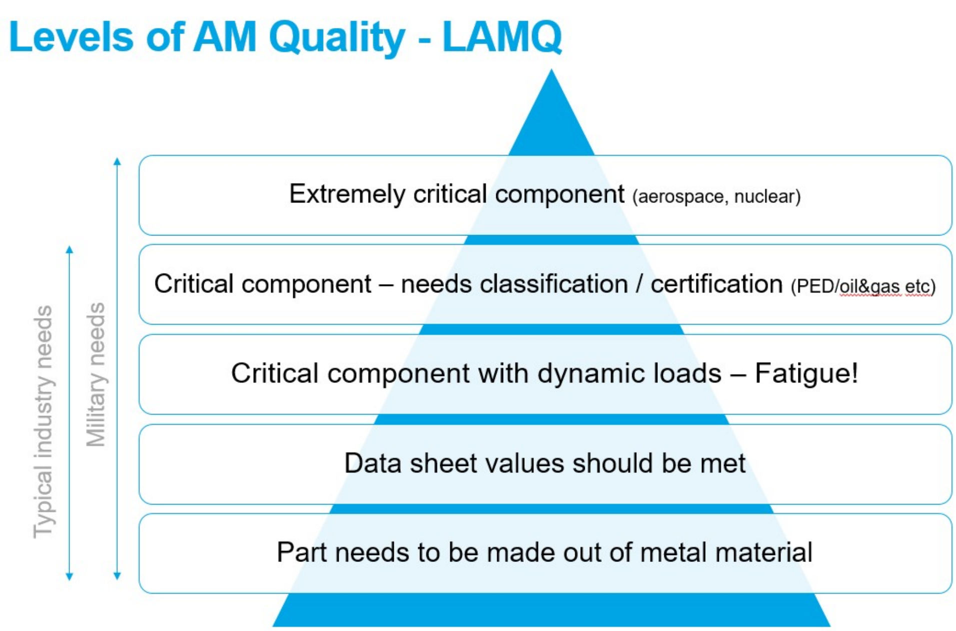


Figure 5. Levels of additive manufacturing quality - LAMQ™ (Etteplan-3DStep).

2 CURRENT STATE OF METAL ADDITIVE MANUFACTURING IN FINLAND

Stereolithography and similar techniques using UV light to cure photopolymers were developed in the beginning of the 1980s, while initial development for metal AM processes started in the 1980s and 1990s (Milewski, 2017). One of the first 3D printers for plastic was delivered to Finland in the early 1990's to Electrolux. Aalto University started research on additive manufacturing already in 1992 and, then Electrolux employee, Olli Nyrhilä was one of the first people to start experimenting the idea of metal additive manufacturing. In light of this, it might seem a bit strange that Finland is not one of the spearheads when it comes to utilizing AM industrially and especially with metals. When having a deeper look into the matter it is not that peculiar; the early adapters of metal additive manufacturing have been the aerospace and automotive industries which Finland does not really have.

In fact the first commercial service bureau for metal additive manufacturing was founded in Finland in 2014. Since then there has been a steady increase in the amount of Finnish metal additive manufacturing service bureaus: a second metal AM service bureau emerged in 2016, a third in 2018 and the fourth and fifth both began operations in 2019.

One of the reasons behind increase in availability of metal AM systems is the increased interest within the Finnish industry. This increased interest was triggered as knowledge about AM that has spread. Nowadays people seem to know what 3D printing is and often even that printing metal is possible. This was not the case even just a few years ago. All this has helped the companies to grow the interest and will to test what AM is capable of.

Technologies being used in the Finnish metal AM market has been in laser powder bed fusion only. So far no company has invested into other techniques such as electron beam melting or metal binder jetting. While LPBF provides the best performance in metal AM components, it is also often the most expensive method. The expensiveness of metal AM tends to be off-putting when companies take their first steps towards metal AM – if their first components are not redesigned for AM or the application has been selected poorly, experience is often that there is no point in using metal AM due to its cost.

Another thing that often rises in discussions is the quality of metal AM components. There seems to be hesitation whether or not the 3D printed metal structure can be trusted – even though the roots of metal AM utilization lies in aerospace and automotive industries where quality matters are taken rather seriously. That being said there is still variability between different service providers in quality and repeatability as the field is still new. Lack of information is also one of the key matters to keep the uncertainty in the air.

2.1 Existing AM ecosystem

The AM ecosystem in Finland has been built upon the research activities of the universities, VTT, and the output of the few service bureaus that have emerged. To complement metal AM, machine shops are being employed to provide final machining for printed components.

As more service bureaus have emerged, knowledge of metal AM has spread and ordering of the first metal prints has become more easily accessible to companies new to this manufacturing technology. For those companies who have already experimented with rapid prototyping and 3D printing of plastics, there may already exist working relationships with the metal AM service bureaus as nearly half of them started by initially offering services in printed plastics.

Of the metal parts being printed by AM service bureaus in Finland, material testing is done infrequently to determine for example density, strength or hardness. Typically such tests are only performed when there are suspicions that the material properties are not reaching the lower limits described by the material data sheets, and usually must be requested by the customer. This means that for high-performance, critical components, there is a distinct lack of knowledge about achievable material properties, necessary post-treatments, needed testing and documentation for verification, etc. These problems are not unique to Finland in the field of metal AM, but are significant roadblocks to the uptake of this technology for critical components.

2.1.1 Service bureaus offering metal AM in Finland

In Finland there are currently five different companies providing metal additive manufacturing as a service. Three of the five provide also 3D printing of plastics and have been in the business the longest. In addition to the five service bureaus, Hetitec in Valkeakoski is specialized in 3D printing sand molds for metal casting. All service bureaus, with the metal AM machines they use, can be seen in Table 2 and their geographical location is shown in *Figure 6*. The materials currently being printed by these service bureaus are among the most common for LPBF, and include maraging steel, stainless steel (316L), titanium (Ti6Al4V), aluminum (AlSi10Mg), and Inconel 718.

Table 2. Summary of metal printers in Finland: service bureaus.

Service Bureau	Location	Machine
3D Formtech	Jyväskylä	EOS M290
3D Step	Tampere	SL 280HL Twin (400 W)
Delva	Hämeenlinna	EOS M270, EOS M290
HT Laser	Keuruu	SLM 280 2.0 Twin (700 W)
Materflow	Lahti	Concept Laser M1, SLM 280HL

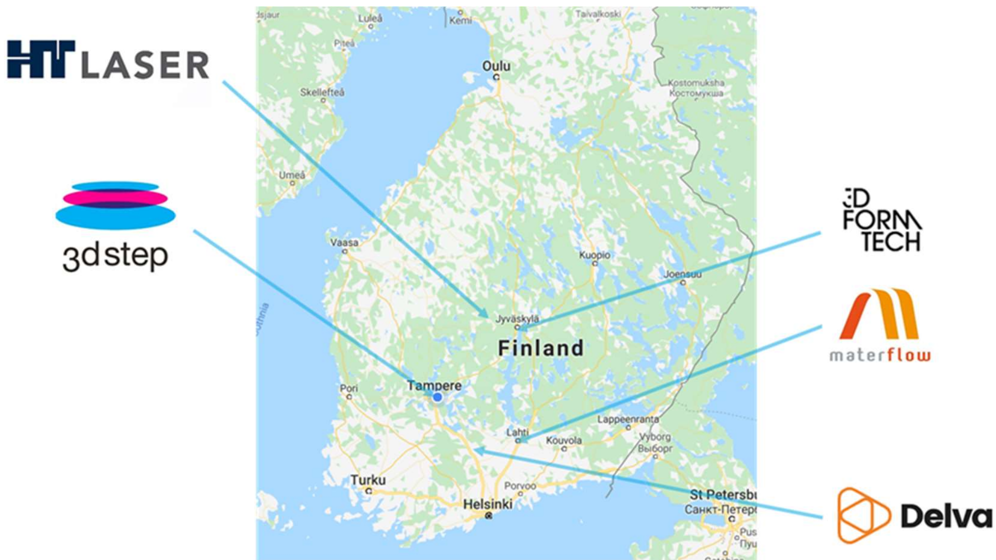


Figure 6. Geographical location of Finnish metal additive manufacturing service bureaus.

As mentioned before, all of the service bureaus in Finland use laser powder bed fusion as their AM technology when it comes to metal. One reason dictating the selection to LPBF is simply that it is the most-used metal AM technique in the world. It also provides parts with the best performance, making it an easy technique to rationalize to customers. It is good to bear in mind though that none of the metal AM techniques, not even LPBF, can serve every possible case optimally. For example very large components are challenging to make with LPBF, and it is not well-suited for large lot sizes due to limitations in build plate size and difficulty to stack components on top of each other. Usually cost is also higher when compared to other metal AM techniques, as was noted earlier in *Figure 2*.

Where PBF techniques (both LPBF and EBM) are very competitive in comparison to other techniques is in part performance and the material properties created. When compared to other techniques it has the best combination of material density, surface roughness and feature size -leading to best overall quality. In critical components this is a good baseline to begin with, but other matters like print process parameters, melt pool monitoring and other material and quality assurances need to be in line with specifications.

Although we currently have five service bureaus operating metal AM machines in Finland, none of them are actually capable of producing the quality required for critical components. The companies founded are mostly so young and fresh that the investment has gone into ramping up the production and gaining customer base rather than honing their quality level higher than level 2 shown in quality pyramid in *Figure 7*. This is understandable as the higher one goes in the pyramid the more money needs to be involved for quality control, material tests, auditing production and so forth. With services available only for the lowest two levels, certain types of customers can be adequately served. However, when companies working with high end applications what to realize the full benefits of AM in their products, they are forced to rely on manufacturing partners outside of Finland.

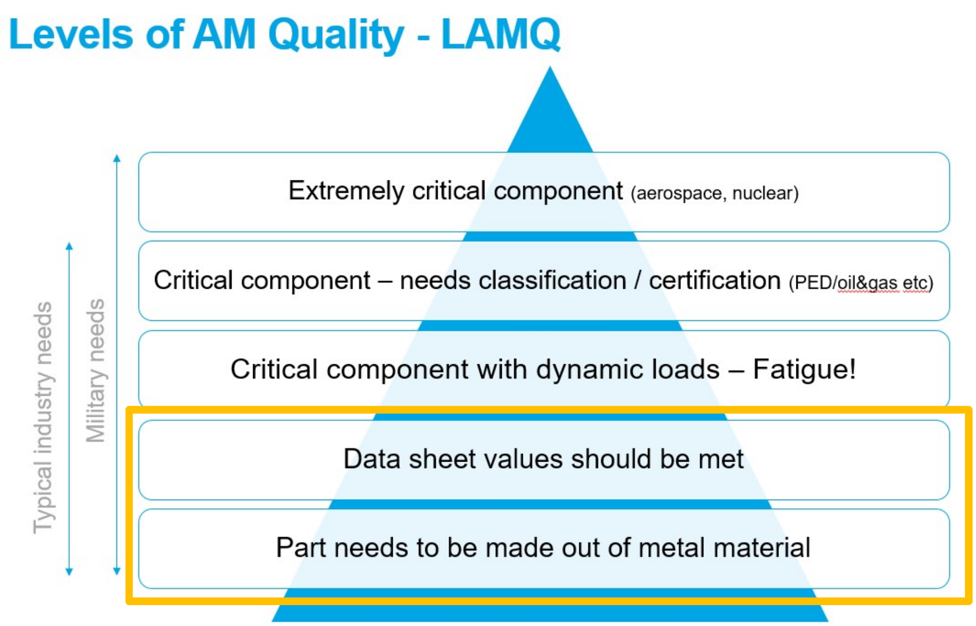


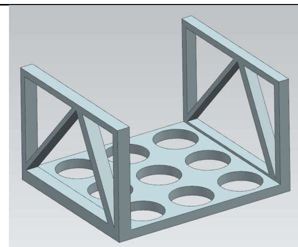
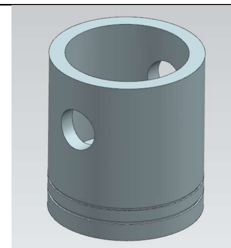
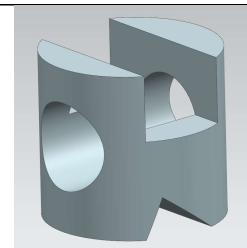
Figure 7. Level of quality in Finnish metal AM service bureaus.

2.1.1.1 Production capacity of Finnish metal AM service bureaus

To give some perspective on lot sizes and annual throughput on a typical LPBF machine, a simple example can be given on a rough scale. A mid-range machine in terms of build plate size, for example equivalent to EOS M290 and SLM280, will be considered. In *Table 3* we can see three sample components and their estimated individual print times that we can use to calculate annual production volume. Printing time varies between material due to different melting speeds, layer thicknesses used, etc., but a mid-range material has been chosen for print time estimation.

If we assume that annual runtime for metal AM machine would be 5000 h we can estimate using the sample components how many pieces we could make annually. Some rough assumptions on setup times have been made and they are included in the individual print time of the component. Results can be seen in *Table 3*.

Table 3. Example components with detailed information on their size, volume and print time.

			
Component	Bracket	Piston	Block
Size	140 x 120 x 85 mm	Ø50 x 56 mm	Ø185 x 170 mm
Volume	115 cm^3	57 cm^3	2180 cm^3
Components per one build	6	13	1
Estimated print time per piece	13 h	4,5 h	180 h
Potential annual volume	420 pcs	1220 pcs	30 pcs

To expand these examples for the complete annual Finnish metal AM capacity we can proceed to do further calculations. Every service bureau in Finland owns roughly the same size machine. From *Table 2* we can see that there are six mid-range machines in Finnish service bureaus (excluding the Concept Laser M1 from Materflow, as it is very small in build area and dedicated to dental applications).

This means that the combined theoretical production volume that Finnish metal AM service bureaus can provide for the sample components would be:

Bracket	6 x 556 pcs	=	3336 pcs
		OR	
Piston	6 x 1250 pcs	=	7500 pcs
		OR	
Block	6 x 43 pcs	=	258 pcs

For the piston this production volume is fair in serial production but regarding the bracket and especially the block it does not seem high enough. It is clear that if production needs for metal AM in Finland would suddenly increase, it would be very hard to answer to this need instantly.

2.1.1.2 Post-print operations in Finnish metal AM service bureaus

As explained earlier, once 3D printing of the component has finished it needs to have the surrounding powder being removed (in powder based metal AM techniques) and the components need to be detached from the build plate. Often components require some heat treatments as well and other post processing like shot peening and machining to finish the component into its final form. In Finland most of the service bureaus have prepared themselves with equipment to perform basic heat treatments, shot peening and detaching from build plate. Depending on a service bureau the ability to perform machining on the components varies from hand held tools to full on CNC milling and turning machines. Machining and heat treatment capabilities have been acquired to serve the customers better and quicker. Looking at components being in serial production, often a third party is being used for machining as it is machine shops core business and they have better suited machinery.

When material tests need to be performed for example to check tensile strength, density or hardness, an external operator needs to be used as none of the service bureaus have acquired such equipment.

When producing components to critical applications HIPping might be something that wants to be done, especially in the aerospace components to ensure minimum amount of voids and pores in structure. So far in Finland only VTT has a HIPping machine for research purposes. To use HIPping as part of manufacturing components need to be sent to other countries like Sweden or Germany.

Some components might require inspection after printing and or machining. There are many ways to inspect a component ranging from visual inspection to 3D Scanning to CT scanning and microscopic inspection to mention few. CT scanning is something Finnish hospitals are familiar with but from industry point of view there is a clear lack of service. Currently only GTK has a CT-scanner in Finland for industrial commercial use.

2.1.2 Metal AM printers in Finnish companies

So far Finnish companies have been very hesitant in acquiring their own metal AM machines, especially to be part of their manufacturing systems. Prototyping is more familiar and more and more companies have purchased their own 3D printers for plastic. They range from cheap desktop printers aimed for consumers all the way to more expensive industrial prototyping machines. This can be seen as a stepping stone and probably will ease up the idea that AM machines would eventually end up on the production floor as well.

To this day there are three Finnish companies who have publicly mentioned to have acquired a metal AM system: Valmet, V.A.V. Group and Lillbacka Powerco. All of these companies use metal AM to help realize their end products but the approach differs a bit. In Valmet’s case they produce molds to manufacture customer specific refiner segment patterns (Valmet Oyj, 2016). V.A.V Group is known for their sealing products and they use metal AM to manufacture some of the tools needed to produce their seals (V.A.V Group, 2017). Lillbacka Powerco is using their metal AM machine to produce end use components to their products.

There might be metal AM machines purchased to other companies in Finland as well but they have not published any public statements about doing so.

2.1.3 Metal AM machines in research centers in Finland

Universities like Aalto in Espoo, LUT (Lappeenranta University of Technology), TUT (Tampere University of Technology) and University of Oulu have all invested into having metal AM equipment. On private sector VTT has acquired the equipment to perform full production chain for powders to be used, to print the produced powder and to do any post processing needed from heat treatments to machining and quality assurance.

On the other end of the spectrum there are some technical colleges who have begun to teach 3D printing using cheap desktop FDM printers in assistance. It is good to see that also high schools and even lower grades have adopted FDM printers as part of their education to inspire AM potential in young minds. To get the full benefit of AM innovative minds are needed and the possibilities need to be taught as early as possible. Steps have also been taken to enable those who don't have access to 3D printers via schools as libraries have adopted FDM printers to their community spaces available for everyone.

In between of these two far ends are academies who have taken the first steps and are now climbing higher. For example Vaasa University, JAMK (technical college in Jyväskylä), Savonia (technical college in Kuopio) and technical college of Turku have all started their process of acquiring at least one metal AM machine.

Academic world seems to be investing into AM quite well at the moment in Finland and that is the right way to go to make Finland rise on the map of utilizing AM. All of the Finnish Research Centers with metal AM machines acquired and planned to be acquired can be seen listed in Table 4.

Beyond the universities and national research center, Finland also hosts the material research center for the largest LPBF machine manufacturer, EOS, in Turku. In Turku EOS validates all of their powder batches for different materials that are sent to customers for use. Also development of new materials for EOS machines happens in Turku and it is possible to order custom materials from them as well.

The majority of the Finnish academia rely on LPBF technique on their metal AM machines but TUT and Savonia are taking a bit different approach by researching also DED techniques. It is important to also study and understand some of the other metal AM technologies, as LPBF is not always the most suitable or even feasible for all applications as depicted earlier in Figure 2.

Table 4. Summary of metal printers in Finland: universities, polytechnics, and research centers

Research Center	Location	Machine
Aalto University	Otaniemi	EOS M290
EOS Finland Oy	Turku	Too many to list
LUT	Lappeenranta	EOS M270, EOS M290
University of Oulu in cooperation with Nivalan Teollisuuskylä	Nivala	SLM 280HL
JAMK University of Applied Sciences	Jyväskylä	LPBF (planned for 2020)
Savonia University of Applied Sciences	Kuopio	Metal X (2019), LPBF & DED (planned for 2020)
SASKY in cooperation with TAMK University of Applied Sciences	Sastamala	SLM 125HL
Turku University of Applied Sciences	Turku	LPBF (planned for 2020)
TUT	Tampere	DED (wire-feed)
University of Vaasa	Vaasa	LPBF (planned for 2020)
VTT	Otaniemi	SLM 125HL

2.1.4 Finnish AM research

There are a large number of metal AM research topics that have been publicly funded and are presently being studied in Finland. Topics include training and education for AM, printing of new materials, aiding and encouraging the uptake of AM in smaller companies, study of metal AM techniques other than LPBF, and use of AM in new and/or highly regulated industries. Other topics, such as 3D finishing of metal components, use of lattice structures, material development, simulation related to AM are also being studied.

Good research in AM is an excellent base when building AM competence within Finland, but it does not mean that we should be satisfied with the research and education being done at the moment. Finland is lagging behind in utilization of AM, thus giving advantage to our foreign competitors. All the research effort requires money of course and therefore public investments to AM should be increased.

One of the reasons e.g. United Kingdom is so far ahead in utilizing AM is the amount of investments they make in AM, as well as the type of industry they have to support it. In *Table 5* it can be seen that the forerunners in AM utilization like US, Netherlands, Singapore and United Kingdom have all made big strategic investments into AM and building AM knowledge. For example in United Kingdom they opened a new Innovation Hub for their Manufacturing Technology Center 15th October 2019 with invested public money worth £11 million (3D Printing Industry, 2019). Making investments into research and manufacturing centers makes sure that there is access to the latest knowledge and if some data is unavailable there are better possibilities to get it.

Table 5. Annual AM investments, population, nominal GDP and filed patents from 2005 to 2011, per country (Ituarte, Salmi, Ballardini, Tuomi, & Partanen, 2017)

Country	AM Public Investment (M€) [A]	Population (million) [B]	GDP Nominal (M€) [C]	Estimated patents filed [D]	Investment / Population [1]	Investment / GDP x 100% in ppm [2]	Patents / Investm [3]
US	160	235	199,591,397.8	900	0.68	0.0802	5.63
China	100	1388	122,494,623.7	780	0.07	0.0816	7.80
Japan	39	126	50,860,215.1	580	0.31	0.0767	14.8
Germany	35	80	37,580,645.1	680	0.44	0.0931	19.4
UK	46	65.5	28,494,623.6	120	0.70	0.1614	2.61
Netherlands	134	17	8,279,569.8	60	7.88	1.6184	0.45
Sweden	10	9.9	5,559,139.78	25	1.01	0.1799	2.50
Singapore	100	5.7	3,193,548.4	20	17.54	3.1313	0.20
Finland	5	5.5	2,569,892.5	10	0,91	0.1946	2.0

[A] Public investments in AM research and technology development. *(Authors estimations, different internet sources and cited public rep*
[B] Population per country in millions of inhabitants *(http://www.worldometers.info)*
[C] Gross Domestic Product (GDP) nominal in M€ *(http://statisticstimes.com/economy/countries-by-projected-gdp.php)[Date: 23 Apr. 2*
[D] World Intellectual Property Report "WIPO," (2015)

[1] Ratio between AM investments and country population. [A] / [B]
[2] Percentage of AM related R&I public investment in relation to the nominal GDP. [A] / [C] x 100% in ppm
[3] Ratio between patent applications and AM related R&I public investment. [D] / [A]

2.1.5 Designing for Additive Manufacturing in Finland

Designing for additive manufacturing (DfAM) plays a critical role when creating or modifying components to be made with metal AM. A deep understanding of the capabilities of the technology as well as its limitations allow a well-trained designer to create innovative, functionally superior components while minimizing the manufacturing costs.

According to Roland Berger's analysis on cost development within AM, in order to become cost competitive with conventional manufacturing for a wide range of cases the cost of AM should decrease by at least a factor of 10. So far signs for such a substantial decrease cannot be seen in the current portfolio of AM technologies, but as this field develops in a rapid pace, one never knows when and what the next big thing will be (Roland Berger, 2018).

This essentially means that simply transforming existing designs to be made by AM is challenging cost wise. To create a successful business cases for AM, a new kind of thinking and designing needs to be done. All companies should bear in mind that the added value in AM nearly always comes from the design.

In Finland there are currently a few engineering offices focusing on designing for AM in addition to the other engineering work they do. The number of AM dedicated people within these companies varies from couple people occasionally working with AM projects to close to ten people doing AM projects full time. The groundwork for design skills for AM is often laid from personal interest or education, but most of it is learned by doing. The level of investment between these firms also varies greatly, as some are taking their first steps into this new technology and learning the basics, while the ones with bigger departments have invested heavily into the knowhow of designing for AM and even how to design critical AM components. Often these engineering companies have plastic 3D printers in-house to support R&D but actual manufacturing is done elsewhere.

As seen in section 2.1.2, a few Finnish companies have acquired metal AM machines of their own, but most of the companies utilizing metal AM produce these components by purchasing them from service bureaus. Their skills in designing for AM varies as well, and is highly dependent on the individual skills they may have.

Since creating complex shapes and new degrees of freedom are possible with AM it is essential that the novel ideas can be realized as well. One of the factors behind successful AM design is in fact being able to 3D model the ideas one gets all the while keeping in mind the functionality of the component as well.

In companies organization wide AM knowledge has not yet been established, but instead the AM knowledge is based on individual competence. The competence is acquired through personal interest and also by education provided by the Finnish universities and technical colleges.

2.2 Education for additive manufacturing in Finnish academia

Additive manufacturing education within Finland is quite well spread around the country, but the level varies: from universities having extensive courses on AM, to secondary schools having an entire examination based on 3D printing and modeling, to technical schools and universities not teaching anything about AM.

As seen in section 2.1.3, some academic institutions have invested into metal AM machinery to support their research and education. The ways in which the metal AM machine is incorporated into offered courses varies, but in general the likelihood of having AM courses offered increases with the investment in a machine.

Having the education of AM integrated in different faculties is important so that more expertise can be provided to the industry and its growing need. Currently there are skilled individuals working with AM in Finland but when talking in broader terms the expertise in AM is very limited, even though there is good research going on. More AM courses are still needed in academies to broaden the knowledge of graduates who move to work in different companies. The number of credits offered in Finnish universities (technical colleges excluded) on 3D printing topics in 2019 are summarized in Figure 8. For the Finnish technical schools such table was not available.

In terms of content it seems that in many schools the level of education includes quite well different technologies and their principal of working. This is especially true with plastic techniques and more and more often including metal techniques as well.

Typically some hands-on experience is gained through exercises where a component needs to be designed and then 3D printed with plastic 3D printing machines. In some cases also metal AM machines using LPBF technique are being utilized but comparing to the amount of machines available in academies this option is used too rarely. There is also a lack of skills and knowledge needed for doing designing for additive manufacturing (DfAM). Some basic rules like the thumb rule of 45 degrees for support-free printing are generally known but deeper understanding of metal AM design rules and the manufacturing chain with different steps and requirements is missing.

To support spreading of AM courses in Finnish academies, universities and technical schools have started to collaborate and share their education materials to each other. Collaboration helps to speed up the process of adapting AM courses to curriculum by cutting off the time needed for material creation.

Considering the whole process of additive manufacturing skillful people are needed also to prepare the files for the print job as well as operating the machines themselves. At the moment the only way to gain knowledge on this is through AM courses where different machines are being used and print preparation actions are needed. Learning to operate the machine is mostly done by doing in service bureaus by having an internship period or for example working as a research assistant in universities.

Regarding the AM training needs industry has for their existing design engineers the variance of offering seems to be wide. LUT is offering AM training within their ME3DI research program to interested participants. In Pirkanmaa area there is also a research project called 3DIndesigner which is focusing on spreading AM design knowledge into small and medium sized companies. Some other universities and technical schools also arrange AM trainings but they are not so frequently available. Other AM training providers include metal AM service bureaus and the most advanced engineering offices.

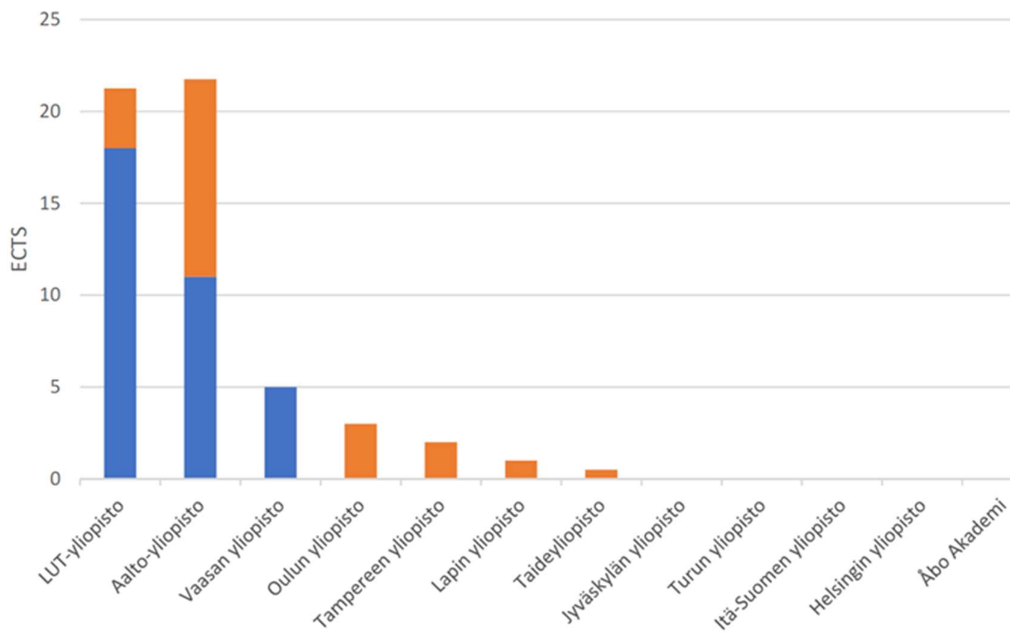


Figure 8. Courses on 3D printing offered by Finnish universities in 2019, measured by number of credits (Piili, et al., 2019)

2.3 AM know-how in Finland

In Finland there is a satisfactory offering for plastic additive manufacturing services for prototyping and end use components. The industry has learned to use plastic AM as part of their product development cycles, first runs of production or even for final components in their products - with the components being printed in-house or bought from service bureaus. The following sections will now summarize the state of metal AM in Finland in terms of what is already being done, what is missing, and existing or potential bottlenecks in industrialized AM production.

2.3.1 Manufacturing

As indicated at the start of this report, LPBF is the primary metal AM technique in use today. In terms of knowledge, research and industrial uptake, this technique has also dominated in Finland. The five existing service bureaus and numerous universities and research institutes with own machines have led to a steadily growing knowledge base and broadening experience related to the operation of LPBF machines. Within Finland there exists expertise related to model processing and build job preparation, material handling, process parameter optimization, and machine operation. The existing infrastructure and knowhow match level 2 on the quality pyramid (*Figure 7*) and it is safe to say that moving up on the levels would require knowledge Finland currently does not possess. Furthermore, there is no such thing as a one-stop-shop for metal AM in Finland, meaning that design, AM production, and advanced thermal and surface post-processing never occurs all at one place.

The limited number of trained experts poses a potentially serious problem in the near future if the demand for metal AM in Finland grows as expected. This is a situation that is common worldwide, thus with appropriate actions taken Finland has a way to move forward in the metal AM game. The amount of courses dedicated to AM needs to be increased across all levels of education in order to ensure knowledge transfer into industry and thus naturally increasing AM utilization organically. Furthermore, experience and training levels vary quite drastically within Finland, and the reality is that currently not all build jobs are created equal.

There are several other interesting metal AM techniques which are essentially unavailable in Finland currently. Although TUT has been studying directed energy deposition and Savonia University of Applied Sciences plans to invest in DED equipment next year, this leaves a glaring gap in ability to manufacture large metal components with AM in Finland. Furthermore, another significant gap exists for lower cost and performance but high lot size metal parts that could be covered by metal binder jetting. Finally, EBM technologies are advancing and should definitely be considered as an interesting alternative to LPBF, producing parts with similar material properties at a much faster rate and lower cost.

2.3.2 Design and build preparation

Due to the efforts by Finnish universities and research institutions, engineering firms, and AM service bureaus there are currently a fair number of people with varying skill and experience levels related to metal AM design and build preparation. As mentioned earlier, should demand for AM parts in Finland suddenly rise however, there would inevitably be at least for some time a shortage of people available to fill these roles. In addition, due to lack of research, course offerings and a service bureau where test parts can be created, there is bound to be a lack of individuals who are able to design components specifically for DED, EBM and MBJ techniques in Finland.

Another challenge when it comes to design and build preparation has to do with available software tools. There currently does not exist a single software tool that can perform all needed tasks well: create easily to manipulate bionic or freeform 3D models, generate infill such as lattice structures for light-weighting, perform FEM and topology optimization as needed, generate needed support structures for printing, run print process simulation to evaluate the printability of the part, etc. Design engineers are thus required to move 3D models between software which makes traceability difficult, can result in lost data during transfer, and means that design changes are sometimes more difficult to produce than might typically be expected. There is the further difficulty that certain design features, such as lattice structures, are often only created with stl file format (triangular mesh) and cannot be converted to more standard CAD file formats. In the past few years the major software companies producing 3D modelling and engineering simulation tools have been fighting to be the first to produce a comprehensive package for AM design, and several of those companies (e.g. Dassault, Siemens, AutoDesk, Ansys, etc.) already offer tools to produce all of the features and conduct needed simulations as described. Unfortunately these tools are often prohibitively expensive and in many cases still require transferring models between various software tools and the use of various file formats, meaning many of the same problems still exist.

2.3.3 Post-processing

As most of the actions related to post processing are the same as are being used at the moment to manufacture components conventionally, Finland already has a pretty good knowledge on them: milling, turning, sawing, and heat treatments are all things being done on a regular basis. Something to point out though, in terms of conventional methods is the shape, material thicknesses and documentation level that AM components bring to the table. As there is yet no standardized way to document metal AM components nor requirements for information needed to transfer, it might take a few test rounds for machine shops to get used to metal AM components.

Some components might require more advanced post-processing methods than used conventionally, which is usually the case with critical aerospace components. For example different thermal treatments like HIP may be used to achieve the desired final properties for the component. Commercial HIP services is something Finland lacks at the moment, and with it the deep knowledge related to that. It is hard to imagine that in the coming years HIP equipment would be acquired in Finland as it is expensive and would require enough volume on the production side to pay off. Before such a service would arrive to Finland, VTT's HIP equipment could be utilized to research the topic.

Usually in metal AM components there are support structures that are needed to be removed after printing and stress removal heat treatment. The removal can be done in a traditional way by hand or as part of a machining operations. More advanced methods are available that streamline the production and reduce the costs in the long run as the amount of manual labor is lessened. Such methods use for example electrochemical processes to remove the supports automatically. They can also be used, along with abrasive honing, to improve the surface finish of a metal AM component which is rough straight after the print process when compared to a machined surface. Currently there are no specialized support removal / surface finish machines in Finland.

2.3.4 Qualified production of critical AM components

Qualifying production of a critical component in Finland currently is extremely difficult if not impossible. Challenges exist in terms of lack of know-how, standardized manufacturing and testing methods, qualified service bureaus, sufficient inspection equipment and expertise, material data, and in general an organized way to move through the entire manufacturing process described earlier in Figure 3. In addition, data transfer and security are unsolved issues that still need to be addressed in Finland and in general (Yampolskiy, et al., 2018). Based on the manufacturing process the biggest areas where Finland is lacking competencies or full understanding can be seen in *Figure 9*.

The typical small or mid-sized company in Finland has no way to tackle all of these problems on their own in the existing local AM ecosystem. Significant and long-term investment as well as industrial backing in this area is required to bridge these gaps in resources, data and expertise.

A bigger more focused AM center would therefore be needed to serve the Finnish industry in all of its AM related matters up to the most critical levels of AM components. It is important to get things going sooner than later as we are currently far behind from more advanced countries in AM utilization. The more we wait the more we give competitive advantage elsewhere not to mention that the most advanced Finnish companies will direct their AM production to other countries.

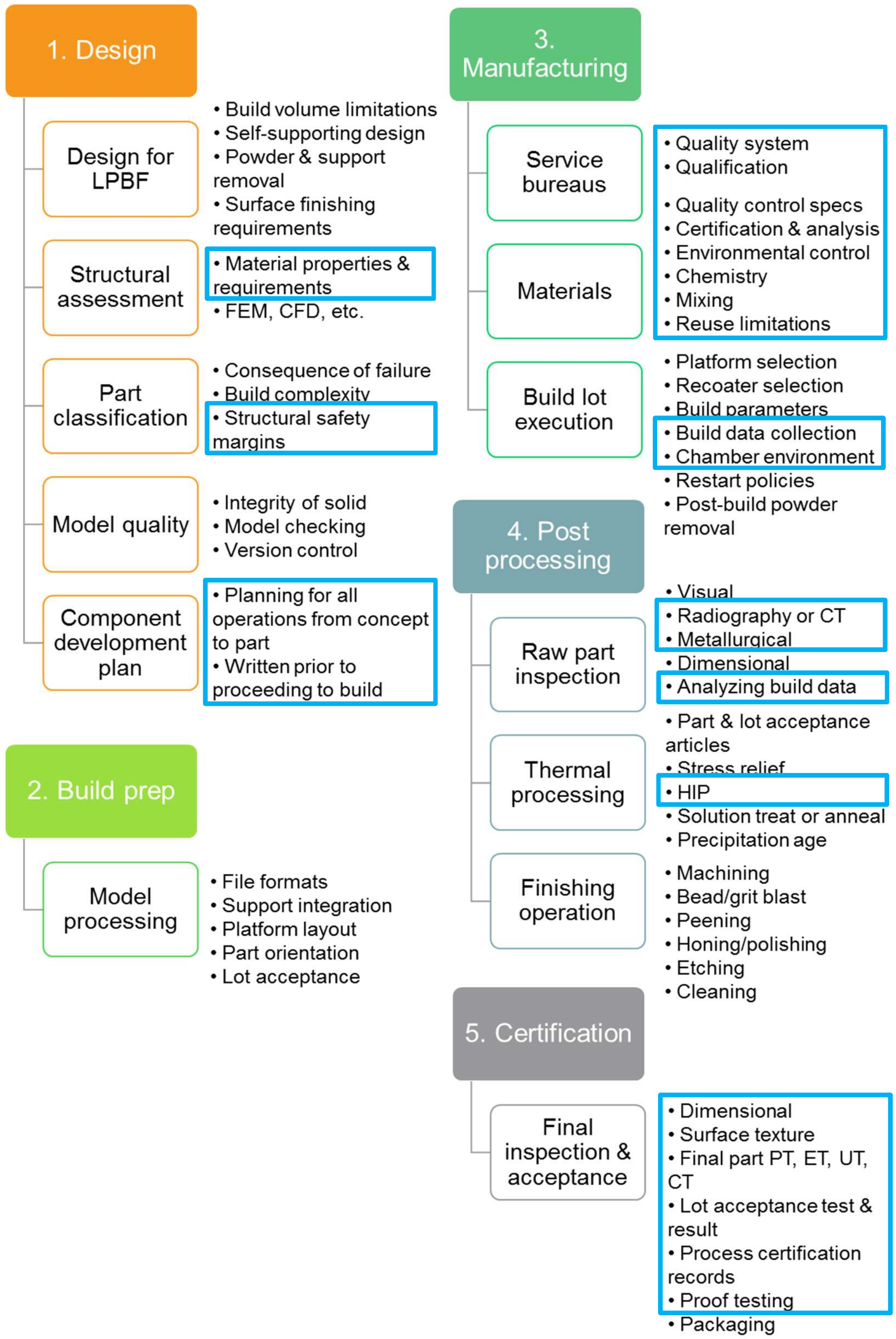


Figure 9. Missing competencies or lack of full understanding that Finnish AM eco-system has when creating a qualified component with LPBF.

3 CONSORTIUM CREATION: HX ADDITIVE MANUFACTURING CENTER OF EXCELLENCE (AMCE)

The challenges that exist with bringing Finland up to speed in the industrial application of metal AM are real. Other countries are facing similar challenges. For example Sweden has listed their findings into "The Strategic Research Agenda for the Swedish Additive Metal Manufacturing Industry" -report (RISE-Acreo, 2018). There is a significant risk that if nothing or too little is done to propel the uptake of these technologies forward, a real opportunity will be missed. The creation of the HX Additive Manufacturing Center of Excellence (AMCE) will help to address the following:

- Additive manufacturing and especially metal additive manufacturing is challenging. There is a large spread in competencies and knowledge in the industry as well as in academia.
- Many companies will struggle within their business models in AM for a long time in spite of having skilled engineers and top management support. Many small and medium sized companies find it too costly to enter AM, some universities have no AM activities at all and only few secondary schools have AM in their curricula.
- Much of the research is done in silos and companies in Finland do not have resources or funding to develop the competencies far enough. The companies who have taken steps in their AM journey face a number of technical challenges that they need to work out on their own. With the Additive Manufacturing Center of Excellence (AMCE) Finnish companies could create a critical mass and more structured collaboration between the stakeholders. Such a critical mass requires collaboration efforts on a national level, with full backing from industry, academia, research institutes and other stakeholders.
- The AMCE can accelerate the industrial adoption of additive manufacturing and help bring a new generation of innovative engineers and products to the market. The excellence center will fill the gaps in additive manufacturing knowledge and this is what Finnish manufacturing needs to take full advantage of the new technology.
- Companies in HX AM Consortium need to commit to do what it takes to reach the highest level in AM, production of critical aerospace components in collaboration with others and with whole Finnish AM ecosystem.

An overview of the proposed AM center of excellence and how it would fit amongst the existing metal AM ecosystems in Finland is shown in Figure 10. The AM center of excellence would be its own unit providing research and education as well as production capacity from its AM factory side. Critical military and aerospace components could be researched and manufactured within the center of excellence. The research and application lab could collaborate also with other Finnish research & application labs sharing information from public research projects and providing knowhow to Finnish industry as well. The AM factory could be used to produce components to Finnish industry as well with the capacity that is remaining after critical military and aerospace production.

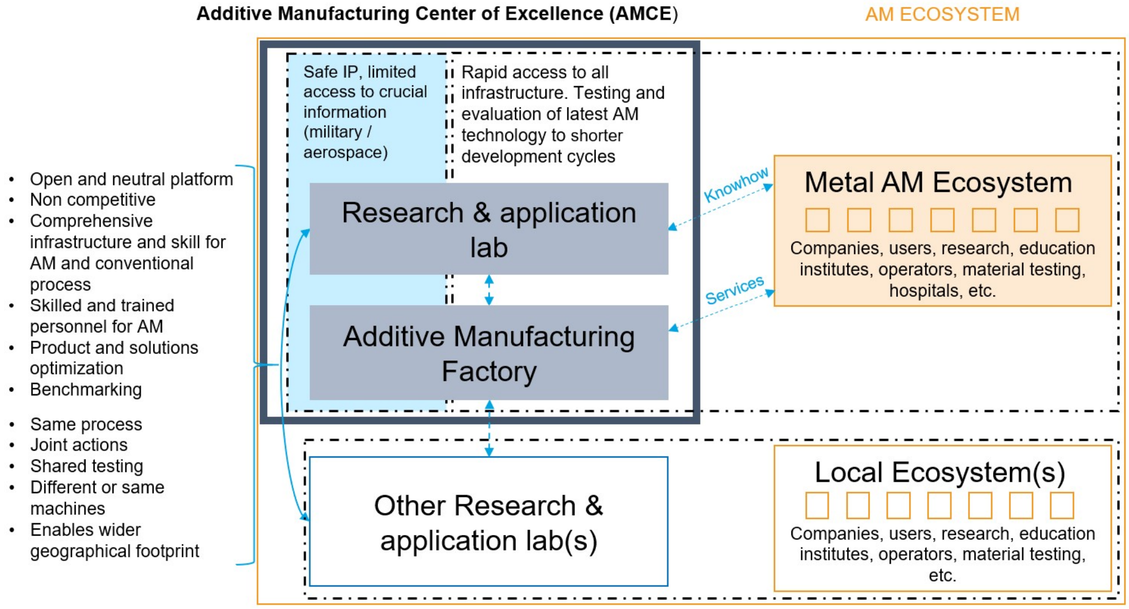


Figure 10. An overview of the proposed AMCE and how it might be connected to existing metal AM ecosystems in Finland

3.1 Consortium roles

In this section the key members of the HX AMCE consortium are identified, as well as the roles that they will play. During the development phase, HX AMCE needs a more closed group of participants that can really propel the planning forward and make needed decisions faster. In the future, the consortium can grow based on industry and research actions and initiatives. An overview of the consortium can be found in Figure 11, with additional details about each role provided in the following sub-sections.

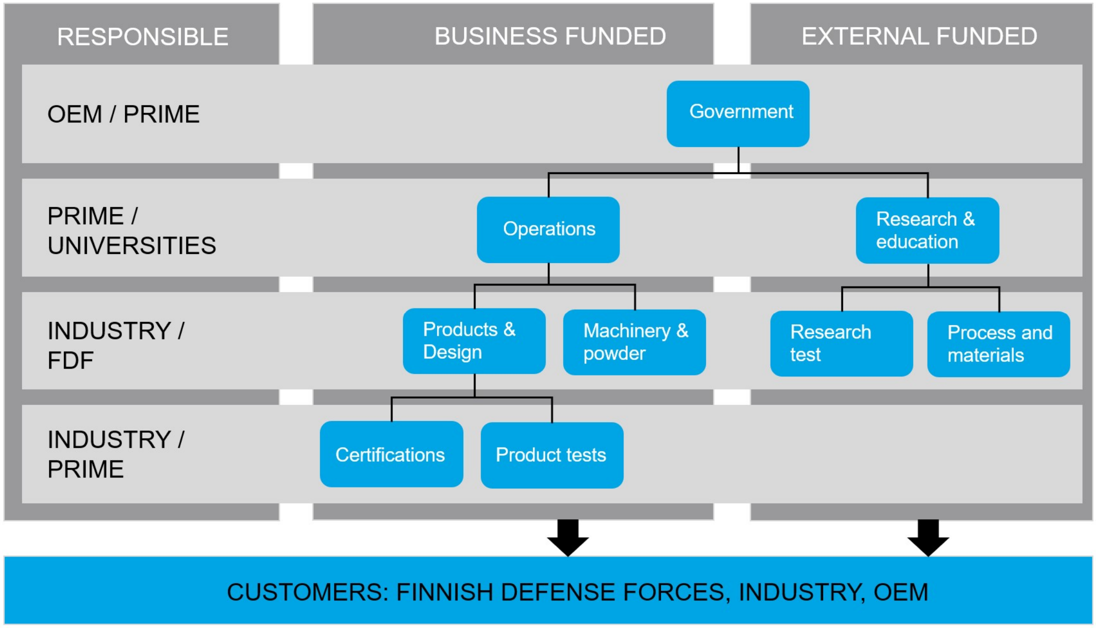


Figure 11. Overview of roles in HX AMCE consortium.(Patria Aviation Oy, 2019)

3.1.1 HX-OEM

It is expected that the selected original equipment manufacturer (OEM) has valuable intellectual knowhow they can provide for the AMCE. The OEM most probably has generated already knowhow that Finnish AM industry could benefit from, such as material knowledge and validation knowledge just to mention a few of them.

By getting access to the research results and processes already generated and validated by OEM to manufacture critical aerospace components, Finnish industry could speed up the adaptation of additive manufacturing by several years.

The serial production side of the AM excellence center could be a copy of one of the OEM’s validated AM factories. This could ease all validation and certification work needed to make sure the production line is suitable for critical component manufacturing. In the future all changes made to the “mother line” could be also made to the production line in Finland.

The OEM might also face the need for certified manufacturing capacity if the metal AM market continues to grow as expected. The AMCE in Finland could be a fully tailored production facility according to the OEM needs, and could work as their manufacturing hub in Nordics. There would also be potential to scale up production to serve other needs the OEM might have.

Additive Manufacturing Center of Excellence as a one-stop-shop for OEM

- Fully tailored production facility according to OEM needs
- Certified production capacity
- AM design service
- Engineering services
- AM spare part service

3.1.2 Prime

The consortium needs a lead company that will work as a prime in all actions related to AMCE. This company needs to be a partner of the Finnish defense forces.

This company should be interested in investing in the AMCE and in serial production capability. This company needs to have a solid value adding role in the FINAF/FDF supply chain and in certification programs due to its complexity. This company sees the potential of additive manufacturing as a manufacturing method and can benefit from local manufacturing in its current and future business.

3.1.3 Finnish Defense Forces

Finnish defense forces has announced additive manufacturing as one of the interest areas in direct or indirect IP related to the HX offer.

Military logistics need to manage products and information throughout a demanding supply chain. The distributed nature of field operations in rural areas increases this complexity further. Additive manufacturing will have a massive impact on the military supply chain, and how it is managed in the near future.

Additive manufacturing will also have a massive influence to logistics chains: instead of moving spare parts from warehouses to the field, parts could be made right on the spot or just raw material (e.g. powder) is delivered.

Troops could eventually have a 3D-printer delivered or located near them inside a container putting vehicles back into battle faster and cheaper. This kind of approach sets new kinds of requirements for troops operating the machines in the field.

Additive manufacturing can change everything from how soldiers fix equipment in the field to how much their weapon systems weigh.

All the research and development efforts by the Finnish defense forces could be continued and carried out in the Additive Manufacturing Center of Excellence. The work with industry could enable a more comprehensive approach. The center could facilitate all needed training defense forces would need, and as a future vision, the AM trainings held during future military service could create new employees within the field of additive manufacturing in Finland.

The defense forces need to be highly involved in AMCE. There is a need for AMCE in Finland to ramp-up needed competencies and services and make sure of the usability of the systems in times of peace and war.

3.1.4 Industrial partners

The consortium needs from one to three AM forerunners from Finnish industry. These companies see additive manufacturing as one of the enablers for their future products and production. Their make or buy strategy will benefit from the AMCE since it enables access to application development, testing and prototyping, and to serial production. In the AM center of excellence companies can benefit from ease of access to verify their design and then decide whether to manufacture the parts locally in Finland or to use distributed manufacturing.

The industrial partners can bring valuable knowhow to the center and the center could also benefit from the industrial partners current and future testing and manufacturing knowledge. The center of excellence would also benefit from the industrial partner participants since their products would bring additional production to the factory and also variation in the produced parts.

Inclusion of the industrial partners would also make sure that key skills related to metal AM production would be spread more widely to industry.

3.1.5 Engineering

Additive manufacturing enables the use of new kinds of shapes and new degrees of freedom. To be able to produce all new features, like for example topology optimized parts and lattice structures, it is needed to learn how to harness these new degrees of freedom during the design process. Continued learning is needed to use new tools to create unseen shapes and products and how to set-up the machine and print parameters. To support the change the center needs skilled team of engineers or an engineering company to carry out engineering related task. A list of typical engineering related tasks are listed below:

AM engineering – Design and validation

- Design for additive manufacturing
- FEM / CFD
- Process simulation
- Reverse engineering of obsolete parts
- Own R&D to support development of devices and equipment for optimization of production
- Ideation workshops
- Business case creation
- Hands-on training for various solutions

Application Engineer - Build preparation

- File verification
- 3D data correction
- Print optimization
- Build supports
- Packing

- Slicing
- Laser control

3.1.6 Machine operating and post processing

Additive manufacturing production differs from production in normal machine workshops. The operators are in a similar role as the material producers for some other technologies. The end material properties are defined during the print process and there is a certain learning curve that all operators must traverse in order to accumulate enough experience to be able to produce high quality parts.

The center would need skilled management and operators. If the center would be ramped-up in a short period of time there most probably would be a lack of skilled personnel available and thus pre-organized trainings should take place. It could also be useful to partner with current service providers who could take part in the center's operations and provide trainings and resources. Lists of typical management and operator related tasks are below:

Management

- Production management
- Project management
- Quality management
- Production supervision

Production Technician – Post processing

- Powder removal
- Sawing / Cutting
- Support removal
- Sandblasting
- Milling
- Turning
- Machining
- Heat-treatment
- HIP
- Advanced post-processing

3.1.7 Testing and validation

Additive manufacturing and especially production of critical parts needs heavy testing. It would be convenient first to study the Prime's and Industrial partners' equipment, skills and competencies to carry out testing and validation. Certain testing needs to be built-in to the critical component manufacturing process, but basic testing could be handled by subcontractors providing the services. Lists of typical testing and validation related tasks are below:

Mechanical testing and materials lab

- Powder testing, powder characterization
- Material testing
- Mechanical testing
- Chemical testing
- Sample preparation

Validation engineer - Inspection & Quality

- 3D measurement system
- Optical measurement systems
- FAI – First Article Inspection
- Liquid penetration testing
- Magnetic particle testing
- Ultrasonic testing
- Radiograph testing

3.1.8 Research and education

The participation of research and education centers is a must. There are four forerunner research units in the Finnish AM ecosystem - Lappeenranta University, Aalto University, Tampere University of Technology and VTT.

These units should be a part of the AMCE. They could be in charge of nationally and EU funded projects. The center would enable them to make groundbreaking research and help produce more AM oriented PhD & MSc students. Units would be responsible to develop skills, competencies and processes to support different manufacturing strategies for enhanced productivity. The center would enable them an access to major metal AM manufacturing technologies.

In AMCE the research would support industrial needs, not only future initiatives. Research and education would also create awareness, basic understanding of AM and success stories in Finnish industry.

3.2 Targets for the consortium of companies in AMCE

- Profitable business
  - Enter the AM to make and grow businesses.
- Technology leadership in Nordics in their business areas
  - Leverage of the skills generated from critical applications to push the boundaries further.
- Access to state of the art manufacturing and latest research
  - Close follow up for the state of the art research enables fast utilization of results.

- Utilization of new manufacturing methods to produce / gain more business
  - New designs, new innovations, better products
- Differentiating from the competitors
  - New services, repairing and showing what being a forerunner is.
- Profiling themselves as industry forerunners to entice more skilled people
  - New technology will rise the interest among skilled people and skilled people will want to work with forerunners.
- Security of supply and the usability of the system in times of peace and war
  - Enabling save production and skills needed.

3.3 Benefits to Finland

Two things become clear when analyzing the current state of AM in Finland and the needed steps to create a qualified critical components (as in Figure 3). First, it is not currently possible to complete all of these steps in Finland. And second, there are huge potential advantages of bringing the equipment and know-how to complete all of these steps into a single environment.

- Increases competitiveness of Finnish companies
  - Increased AM know-how leads to new innovations
  - Better and more cost-competitive products
  - Increased creation of added value
- Creates foundation for completely new industry in Finland
  - Opportunity for Finland to be an early adopter of AM
  - High-technology manufacturing - increased creation of added value
  - Huge export opportunity due to the nature of AM
  - Lost traditional factory jobs can be replaced by new AM factory jobs
- New high-paying jobs created
- Provides excellent facilities for high level research work
- Crucial contribution to security of supply

4 BUSINESS CASE FOR AN ADDITIVE MANUFACTURING FACTORY

This chapter investigates whether a “larger” production site is feasible and what revenue would be needed to run a financially sound manufacturing.

4.1 Additive manufacturing market

As established earlier, the time for additive manufacturing has finally come and AM is being hailed as a game changer for 2020s. EY has identified key findings of AM to be e.g. it's ability to boost competitiveness and production is moving closer to customers. Cost, however, is still holding adoption of this manufacturing technology back. All the key findings can be seen in *Figure 12* (EY, 2019).

- **3DP use is escalating.**
  65% of businesses surveyed have experience of additive manufacturing (AM) – up from 24% in 2016.
  Four out of 10 have in-house systems in place.
- **The West is losing ground.**
  Germany, which had the highest exposure to 3DP in 2016, has become one of the countries with the least experience.
  The US has the third-lowest experience of AM.
- **Asia is surging ahead.**
  More than four out of five (81%) South Korean and 78% of Chinese firms have used 3DP – up from 24% in 2016.
- **Aerospace tops sector use.**
  More than three out of four (78%) aerospace companies apply 3DP – more than any other industry.
- **Businesses adopt exploration mode.**
  39% of companies are at maturity Level 2 with AM; experimenting, testing, and identifying how it could benefit them and via which applications.
- **The "early majority" – the cohort crucial to a technology's success – are now using AM for end-use parts.**
  18% of companies currently apply AM for this purpose, 46% expect to do so by 2022.
- **Cost is holding back adoption.**
  90% say the high cost of AM materials is inhibiting them, with 87% citing high machine costs.
- **AM is boosting competitiveness.**
  43% say it helps better meet customer needs. By 2022 this number is expected to rise to 56%.
- **Production is moving closer to customers.**
  65% expect to move manufacturing downstream with AM.
- **The 3DP market is expanding fast.**
  Player numbers are spiraling, as traditional industrial players and numerous start-ups enter the arena, and annual CAGR hits 29%.
- **M&A activity is strong.**
  42% of recent transactions involved AM companies buying competitors, 28% saw strategic players entering the market.
  Activity is set to remain robust with 11% of all surveyed companies intending to enter the market.

Figure 12. Key findings of AM development (EY, 2019).

To have an estimation of the potential of the Finnish AM market, it is necessary to understand how AM potential is being projected globally.

Wohlers Associates, Inc. is a 33-year old independent consulting firm based in Fort Collins, Colorado. The company provides technical and strategic consulting on the new developments and trends in rapid product development and additive manufacturing. Much of this guidance has dealt with industrial applications, what works and what does not, hidden costs, industry trends, and growth forecasts.

For 24 consecutive years, the company has published the Wohlers Report, which provides a worldwide review and analysis of additive manufacturing and 3D printing. The report has served as the undisputed industry-leading report on the subject for more than two decades. Many have graciously referred to it as the "bible" of 3D printing.

Wohlers indicates that the global manufacturing market in 2019 is $12,8Trillion of which **0,077%** represents the AM market.

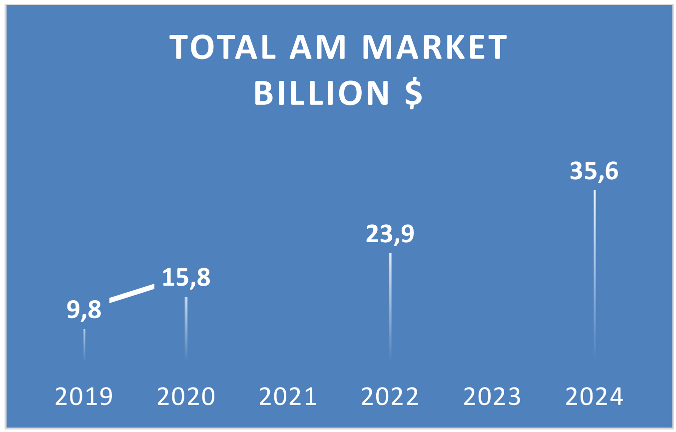


Figure 13. Forecast for all AM products and services worldwide (Wohlers T. C., 2018; Wohlers, Campbell, Diegel, Huff, & Kowen, 2019)

To estimate the additive market in Finland the global observations and forecasts in the 2018 and 2019 Wohler's reports have been applied to the GDP derived out of the industry.

Assuming the global manufacturing market stays constant the AM market share can be extrapolated annually from Figure 13. If the theoretical AM market share is applied to the GDP from the manufacturing industry in Finland, the AM potential in Finland is (annual GDP growth assumed to be historical 1,0%) as shown in Figure 14.

Figure 14. Predicted AM potential in Finland based on worldwide forecast growth and Finnish manufacturing GDP

4.2 HX AMCE machine bases

As there are no information regarding the components to be produced a number of high level assumptions has been made in dialogue with the potential stakeholders. The result is a theoretical exercise in what can be. It is deemed to still serve its purpose and in addition highlight what key success factors and risks there are.

Costs and capacities are calculated with today's values and then a future improvement factor has been applied to for example productivity. What this means is that products available today are used for different calculations and estimations. These will, however, most likely be replaced by superior products at the time of ordering equipment for the potential factory in question.

The core of the production is purely based on metal printers, and aim is to produce near net shape geometries. Components to be produced are assumed to mainly to be of advanced and complex nature, subject to high mechanical loads and or thermal stress. In addition, there would roughly be a measurable portion of the revenue derived from repair applications, at least initially.

By creating value like, but not limited to, minimizing cost for post processing a cost out is achieved on direct production cost, COGS. Other examples could be value from shortened lead time, less need for keeping parts on stock, larger flexibility in terms of part variance etc.

The backbone of the production is the capacity equivalent to 40 high productive printers available today. Several AM technologies are assumed to have its natural place in any future AM factory as different technologies excel in different areas. The learning curve for different technologies as well as the ease with which components can be qualified for a specific AM technology has been factored in when deciding the ramp up scenarios.

Critical to any future factory aimed at additive manufacturing is to choose machines that are well suited to an industrial context where uptime and MTBF are verified as well as ease of use. Transparency or openness in understanding functionality, access to data and parameters are of course a must to enable monitoring of quality and to support in solving NCRs and aid in RCAs. Short turn around, set up and service outage times are of essence why it is recommended to, during the detailed planning phase of the factory, perform a benchmark of the machines considered to validate foot print, media consumption, printing quality and turnaround times.

Main Equipment

Would the equipment be sourced today the following technologies should be considered:

A **DMD** machine with the main purpose to fulfill the repair needs as producing new material volume is fast and cost efficient and can be applied to large components.

Binder Jet for small and highly detailed components seems to be a very interesting candidate.

Due to pure productivity it is questionable if smaller **LPBF** systems with build area of less than 500 x 500 mm will be needed in a serial production context, outside markets with very small components. Larger, truly industrialized, **LPBF** systems are more or less nonexistent today. The attempt at addressing the market needs are showing promising results.

EBM will see a significant increase in productivity during the next few years and will be the main workhorse producing the largest portion of production volume.

Facility requirements and/or infrastructure is covered to the degree that CAPEX/OPEX budget has been estimated for infrastructure like compressed air, electrical system, HVAC system, argon system. A building is assumed to be available or the investment is handled outside this project but funded by OPEX in through rent.

Logistics needs are met by either an overhead crane system or automated fork lifts.

Post processing are calculated to a minimum. Primarily machining with an advanced CNC machine and cutting parts of build plates has been considered. With a high probability there will be a need for heat treatment. In the business case there is budget for a HIP and the idea is that one chooses to focus on either HIPing or assorted heat treatment methods. A sinter oven for the binder jet process is in all cases included.

Powder handling system is needed to manage powder in a as closed loop as possible during the complete production process. Powder removal and management is associated with high costs but can be optimized to a high degree to not significantly contribute to the production cost while maintaining a "best in class" work environment.

4.3 Main assumptions used in the calculations

The ambition has been to be realistic, leaning towards conservative, in all estimations and if in doubt add a safety margin on top rather than distributed on each line item.

	2022	2023	2024	2025	2026	2027	2028
AM Factory							
Infrastructure							
Building adaption and infrastructure	########	########	########	########	########	########	########
Powder management	########	########	########	########	########	########	########
Automated transport system	########	########	########	########	########	########	########
Forklift, furniture and tools	########	########	########	########	########	########	########
Post processing							
	########	########	########	########	########	########	########
Printers							
	########	########	########	########	########	########	########
SUM	**4 200 000**	**8 400 000**	**7 600 000**	**4 000 000**	**1 700 000**	**1 500 000**	**1 400 000**

Figure 15. Forecasted capex budget.

Investment to realize the production estimated at CAPEX ~**30M€** and OPEX **0,5M€** over a period of 7 years. Productivity will increase over time and is reflected by decrementing the cost of printers over the years. The cost of metal powder is deemed to drop as the volumes for AM powder increases, this is reflected in the BC by decrementing the annual cost of powder

When the factory has reached full production capacity and fully mature operations the revenue is predicted to be **30M€** and cover between 10-12% of the domestic AM market.

Revenue ramp up:

	2022	2023	2024	2025	2026	2027
Revenue (k€)	6 000	11 000	16 000	22 000	28 000	30 000
CAGR p.a.		83,3%	45,5%	37,5%	27,3%	7,1%

The investment is financed by bringing in outside capital at an interest rate. All equipment is assumed to be bought and owned by the factory, the option to lease or rent has not been investigated.

Production and process has to be qualified elsewhere and then, when fully qualified, transferred to the factory keeping risk and delays from the shop floor. To achieve this it is assumed that there is a parallel investment in to a AM Research and application lab, estimated to be between 4,5 and 7,5 M€. Investment in the R&D Lab considered to be a strategic R&D investment. The R&D lab would need to have a wide spread of AM technologies and focused on qualification of components for production or high TRL/MRL research. To achieve this equipment for powder characterization, micro structure analysis and limited mechanical testing is needed.

Printers:		2021	2022
Binder Jet			
	# of machines	1	1
EBM			
	# of machines	1	2
SLM			
	# of machines	2	2

Figure 16. Number of machines foreseen for the AM Research and application lab.

To create an income statement SG&A is set to 10%, other costs are estimated at 2% and R&D costs are set to 4%. The R&D costs are aimed at develop the production, gaining efficiency and eliminating quality issues.

4.4 Results

In dialogue with the potential stakeholders it was agreed to base the calculations on a given production capacity and a reasonable production ramp up. The scenarios were evaluated by creating theoretical income statements and balance sheets. This in order to find out where the breakeven point lies and the optimum ramp up scenario.

The conclusion drawn is that, as with almost all BCs, revenue early is better than revenue late and spending late is better than spending early, the later up to a point. This means that we need to achieve a financial escape velocity in the BC by an aggressive ramp up the first few years and to try to make all investments needed fairly early, dragging them out to far time wise proved negative.

	2021	2022	2023	2024	2025	2026	2027	2028	2029
Revenue		6 000 000	11 000 000	16 000 000	22 000 000	28 000 000	30 000 000	30 000 000	30 000 000
COGS		########	########	########	########	########	########	########	########
Gross Profit		########	########	########	########	########	########	########	########
Gross Margin									
Operating expenses:									
SG&A		########	########	########	########	########	########	########	########
R&D		########	########	########	########	########	########	########	########
Depreciation		########	########	########	########	########	########	########	########
Other Costs		########	########	########	########	########	########	########	########
Total operating expenses		########	########	########	########	########	########	########	########
EBIT (Operating profit or loss)		########	########	########	########	########	########	########	########
EBIT %		########	########	########	########	########	########	########	########
Interest income		########	########	########	########	########	########	########	########
Interest expense		########	########	########	########	########	########	########	########
NOP (Net Operating Profit)		########	########	########	########	########	########	########	########
NOP %		########	########	########	########	########	########	########	########
Income tax expense		########	########	########	########	########	########	########	########
NOPAT		########	########	########	########	########	########	########	########
NOPAT %		########	########	########	########	########	########	########	########
EBITDA									
Du Pont									

Figure 17. Example of the template for the income statement used when evaluating the investment

In addition a cash flow analysis was done to evaluate payback time and IRR. The later came back at 24%. Considering the input data it was not deemed relevant to use the pay back method. One could argue that as we suggest annual capex investments 2022 to 2028, 7 years in a row, and we reach a positive accumulated cashflow in 2027 with one additional year left with investments the project is paid for when it ends.

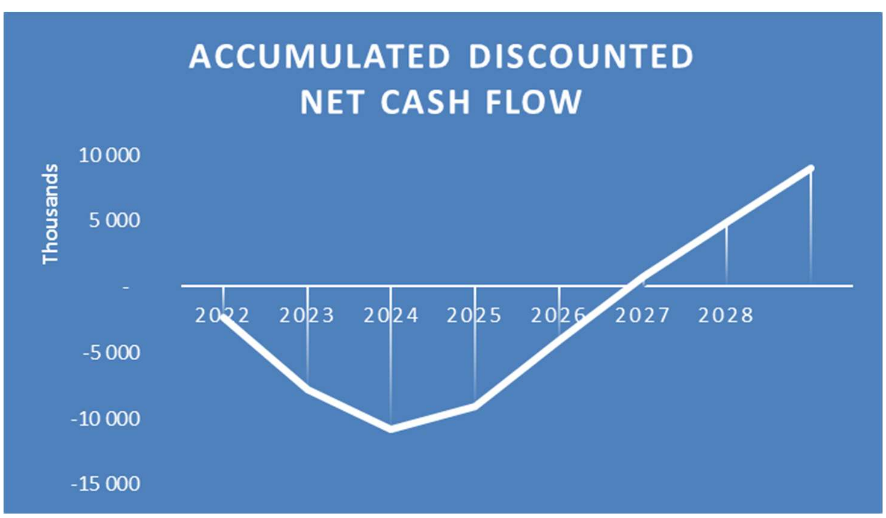


Figure 18. Accumulated discounted net cash flow of the theoretical investment

Lastly a sanity check was made by creating the COGS bottom up to see of the overall income statement could be deemed reasonable.

The HX-program is an unique opportunity to create industrial-scale additive manufacturing expertise in Finland, which serves and develops Finnish defense and security industry expertise, and also brings technical expertise for use by other industries. Direct or in-direct Industrial Participation (IP) projects targeting additive manufacturing would enable faster implementation and validation of this new manufacturing technology. With the investment of 6 M€ to an application lab, a technology transfer from research to industry would enable Finland to reach the Central-European AM level and industrialize AM in Finland. And by investing 30 M€ to a serial production factory, healthy business could be made if revenue expectations are met.

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Etteplan provides solutions for industrial equipment and plant engineering, software and embedded solutions, and technical documentation solutions to the world's leading companies in the manufacturing industry. Our services are geared to improve the competitiveness of our customers' products, services and engineering processes throughout the product life cycle. The results of Etteplan's innovative engineering can be seen in numerous industrial solutions and everyday products.

In additive manufacturing Etteplan combines expertise with our company-wide excellence in the fields of engineering, simulation and mechanical design to offer our customers a comprehensive set of services related to the creation of additive manufactured goods. By choosing the right experts for every project, we are able to tackle even the most challenging engineering or manufacturing problems.

Etteplan has service offerings to help ensure the efficient implementation of AM:

- AM screening – We provide careful analyses of existing products and assemblies, along with creation of business cases to support decision-making and understand the full AM potential of your product portfolio
- AM engineering (adaption or design for AM) – We work closely with the customer to modify or redesign an existing product for AM. For each project we organize a multidisciplinary team to take a simulation driven design approach, using topology optimization, FEM, CFD, and print process simulation during the design process.
- New product development – We work together with our customers to invent new products utilizing the design freedoms of AM to gain competitive advantage and meet future end-user requirements
- AM training – From basic to advanced AM trainings offered on-site, with tailormade training packages from 1-10 days designed for designers, engineers, managers, strategic buyers, etc.
- AM purchasing support – A history of working with an extensive network of service bureaus along with our own AM cost calculation tool means that we can readily help our customers with initial AM purchases while ensuring that they receive a competitive price and high-quality end products
- AM factory consultancy – Highly experienced advanced manufacturing experts will help plan or improve set-up of AM production for R&D, repairs or serial production. Project scope can vary from concept generation and planning through full turn-key factory.

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