State-of-the-art for Additive Manufacturing of Metals

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Executive Summary

This report is a first step in creating a roadmap for the field of research and innovation to promote the industrialization of additive manufacturing (AM) of metals in Sweden. The creation of this roadmap is initiated by the strategic innovation program for Metallic Materials, in collaboration with Vinnova. In this report the focus is on the worldwide state of the art for metal AM, with a particular focus on how the situation looks in Sweden. The report has a focus on Swedish activities and the areas of strength in Swedish industries. Swedish areas of excellence include, for example, materials and powder, manufacturing and automation, design and digitalization.

This report includes an overall exploration into the state of the art for various fields of metal AM. It has been found that the adoption of metal AM in Sweden, over the last few years, has gained acceptance, and that numerous universities and institutes are active in the field. Creation of arenas and collaborations has also helped to grow the use of metal AM. Areas such as aerospace, medical devices, energy and engineering industry segments have been explored to find the challenges and drivers for the full potential use of industrial AM.

It has been identified that industrialization of AM is progressing fast, and that numerous fields have full serial production using AM today. Common challenges have been found to be:

- Lack of sufficient competence
- Lack of standards and certifications routes
- Lack of available materials
- Process robustness
- Productivity & cost

Based on these challenges, the subsequent focus of this road-mapping work will be to take inspiration in these challenges and identify how Swedish industry relates to these. The focus will be on research questions and challenges for Swedish enterprises and organizations that will demonstrate the benefits of using AM and speed up industrialization of metal AM in Sweden.

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1. AM roadmap purpose - focus on opportunities for Swedish industry

The additive manufacturing (AM) of metals has taken a huge step towards industrialization over the last few years and the area is growing rapidly. The industrialization started with dental products and medical implants, which was then followed by aerospace. The Swedish industry is now considering the implications and opportunities of AM within their respective business segments. In some areas, full scale production is already in place. This has given rise to an increased need for research on different topics and on different technology readiness levels (TRL). As Sweden is a small country, it is important to have coordination, and a roadmap for the industrialization of metal AM components, and in developing raw materials for specific applications in Sweden.

1.1. How can AM contribute to "smart industry"

The Swedish Ministry of Enterprise and Innovation has in "The strategy for Smart industry - a strategy for new industrialization for Sweden" [1] pointed out four focus areas, in which AM will clearly contribute to all four. The strategy is to strengthen companies' capacity for change and competitiveness.

1. *Industry 4.0 – Companies in the Swedish industrial sector are to be leaders of the digital transformation and in exploiting the potential of digitalisation*

AM is an ideal technology to build fully digitized production systems on. The production method is based on digital data as input, and because it is a relatively new production method, the distance to a fully digitized production is not as long as it is for traditional production systems. Traditional production systems already have (sometimes obsolete) data handling systems and will require great effort to change.

2. *Sustainable production – Increased resource efficiency, environmental considerations and a more sustainable production are to contribute to the industrial sector's value creation, job creation and competitiveness.*

As material is added where needed, in contrast to subtractive manufacturing, AM will contribute to sustainable production.

3. *Industrial skills boost – The system for supplying skills is to meet the industrial sector's needs and promote its long-term development.*

AM is a hot topic, which attracts skilled students and multi-disciplinary researchers. The existing university courses in AM are overbooked by equal numbers of men and women.

4. *Test bed Sweden – Sweden is to lead research in areas that contribute to strengthening the industrial production of goods and services in Sweden.*

AM test bed facilities exist in Sweden and are expanding. AM machines for metal are still expensive, which make test beds and service centers attractive for companies that are in the exploration phase. With AM it is possible to quickly manufacture prototypes and to iterate the design a number of times, without a great start-up cost. Once the design is finished, the production can be set up with suitable production methods, depending on the number of parts, complexity etc.

1.2. How can AM contribute to overcome our grand societal challenges

The three horizontal societal challenges identified by the National Innovation Council are digitalization, life sciences and environmental and climate technology. These are central to the Swedish transition to a more climate-friendly world. The government's strategic innovation partnership programmes are an effort to find innovative solutions to many of today's major societal challenges. It is about new ways to travel, do business, live, communicate and protect and preserve the earth's resources and ecosystems. The five programmes are:

1. The next generation's travel and transport
2. Smart cities
3. Circular and bio-based economy
4. Life sciences
5. A connected industry and new materials

In "A connected industry and new materials" AM has been identified as one focus area, and a subgroup has been formed.

AM is considered a "green technology" compared to most conventional manufacturing of metal components, both because of waste reduction and energy consumption. Another important resource efficiency feature of AM is the enabling of the remanufacturing and repair of parts. The contribution of AM to digitalization has also been mentioned in the previous section. Furthermore, AM gives us a way to speed up the development of new better materials and also be able to manufacture with currently difficult or impossible materials. This will have a positive impact on the sustainability of products.

1.3. How can AM contribute to goals for the "metallic materials agenda" (strategic innovation program for metallic materials)

The agenda's vision

The Swedish metals producing industry will be a key player in the world's quest to shape a better future. This means that its customer offerings will be at the technical, economic and environmental leading edge and be developed by driven, dedicated and innovative people, at the same time as the manufacturing processes will have minimum environmental consequence.

Seven steps towards renewal, growth and increased competitiveness
To achieve the vision this agenda sets out seven key steps:
1. Develop market offerings √
2. Open up the value chain √
3. Accelerate materials development √
4. Increase flexibility √
5. Improve resource efficiency √

6. Reduce environmental consequences √
7. Boost industrial competence and appeal √

AM contributes to all those seven steps, and the initiative to make a roadmap for the industrialization of metal AM in Sweden was taken from the strategic innovation program for metallic materials.

1.4. Benefits with AM (state-of-the-art & future vision) also managing high expectations

Some of the main benefits of AM include less waste, new design possibilities, increased functionality of the products, and flexible production. Examples include complex parts that are expensive, or impossible, to manufacture by other methods, parts consisting of many consolidated separate pieces into a single component that can be manufactured directly, tools with curved cooling channels for optimized cooling, and light-weight topology optimized parts. Great examples are presented, from all around the world, with very high weight reduction, greatly reduced lead times, costs and waste compared to conventional manufacturing. A side-effect from this global hype is that this can lead to too high a general expectations of the technology, and the challenges in actually implementing them are not always foreseen.

The purpose of this report is to assemble the state-of-the art of metal AM as input for the roadmap. The focus of the report is on Swedish stakeholders and Swedish initiatives and international perspectives are presented only selectively, i.e. only important/large international stakeholders and initiatives have been described. Both drivers and challenges to the adoption of AM have been described.

2. Background

2.1. Overview of other roadmaps, platforms, investigations etc.

Sweden
The first comprehensive approach to AM came in 2014 when an agenda was funded by VINNOVA. The agenda scope was to identify the possibilities and limitations for AM in Sweden. The agenda, and a short film, can be found at: http://www.er.umu.se/am

Vinnova published a report called "*Digitalisering av Svensk Industri*" in January 2016 [2]. This report focused on the digitalization of Swedish industry. As one of seven areas, AM was identified as an area where challenges are: limited research activities compared to a global perspective, and a use of the technology limited to prototypes. It was suggested that, in Sweden, the field of AM research should focus on:

- Education, (i.e. courses in universities and availability of 3D-printers in public schools)
- Innovation and research (create research programs and optimized usage of AM)
- Test beds (develop national test centers for AM, and promote funding possibilities for SMEs)
- Collaboration (collaboration between strategic innovation programs and value chain)

The Ministry of Enterprise and Innovation published a report in 2015 focusing on a smart industry. AM was identified as a revolutionary technique that will have the potential to transform production. It was also identified that new production competences are needed to support the technology development and its industrialization.

International

For Europe, the most cited and used roadmap is the "*Additive manufacturing: Strategic Research Agenda 2014*" [3]. This roadmap was written by the collaborative AM-Platform European project. The roadmap lists various markets and their specific challenges and opportunities. Recommendations for research important to Europe from this roadmap cover the following areas (examples in brackets): Productivity (increased build speeds etc.); Materials (tailored materials for AM etc.); Process & Stability (develop "right the first time" processing); Product quality (in-situ sensors); Environment (validation and standardization of recycling); Standards & Certification (certification processes); Training & Education (develop specific AM-training); Others (Collaboration).

Other roadmaps and research agendas have also been made in the following countries and regions and can be found as references here:

- Australia
- EU
- Finland
- Japan
- Germany
- UK
- USA

One challenge that is profound to much of the work within the field of AM was highlighted in the Finnish roadmap:

"The disadvantages of field research and case research are that companies will not necessarily share their knowledge, successful applications and study cases will be seen as a commercial competitive advantage against competitors."

2.2. Definitions and process terminology

The terminology used in this report will follow the standards SS-EN ISO 52900:2016 [4] and SS-EN ISO 17296-2:2016 [5]. The AM terminology is mainly regulated in standard SS-EN ISO 52900:2016, "Additive manufacturing – General principles – Terminology" while the main focus of standard SS-EN ISO 17296-2:2016 "Additive manufacturing – General principles – part 2: Overview of process categories and feedstock" [5] is process categories.

Additive manufacturing (AM) is defined as follows, in the standard SS-EN ISO 52900:2016:
Process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies.

Standard SS-EN ISO 17296-2:2016 lists seven basic process categories that are defined as follows.

- Vat photopolymerization - additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.
- Material jetting - additive manufacturing process in which droplets of build material are selectively deposited.
- Binder jetting - additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.
- Powder bed fusion - additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.
- Material extrusion - additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.
- Directed energy deposition - additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.
- Sheet lamination - additive manufacturing process in which sheets of material are bonded to form an object.

Out of these seven categories Vat photopolymerization has, so far, not been used for metals. But, as it is currently being used for ceramics (with photopolymer resins that are impregnated with ceramic powders, and then transformed into pure ceramics in a secondary furnace sintering process), it too, has the potential to, one day, be used for metal.

The following abbreviation will be used in this report:

- PBF-LB Powder bed fusion with laser beam
- PBF-EB Powder bed fusion with electron beam
- DED Directed energy deposition

These abbreviations are not yet- included in any standard, but the Swedish SIS technical group for AM believes that they will be in the near future.

3. Stakeholders

The stakeholders for metal AM from research organizations, industry and society are described below. SVEAT is the association for additive manufacturing in Sweden with 36 members from industry, institutes and universities and with the overall goal is to promote AM in Sweden. SVEAT, however, also deals with groups with interest in materials other than just metals.

3.1. Research

3.1.1. Sweden

The first research in metal AM in Sweden was performed at KTH (tooling), Swerea IVF (Fcubics/Digital Metals), Chalmers (Arcam) and at IUC Karlskoga (EOS and material development) and resulted, for example, in several patents [6], [7]. Research was also undertaken on direct casting of tools by Swerea IVF and Swerea SWECAST using 3D-printed sand molds. This was around the year 2000 but, due to lack of funding, this was followed by a period of lower activity. The first university in Sweden to start up a more research active program within metal AM again was Mid Sweden University (PBF-EB, medical, sports technology) in 2006, followed by Stockholm University (PBF-LB, materials), University West (DED, process control) and Chalmers (materials, powder). Over the last few years, some of them have invested in their own machines. Other universities have also started activities in

AM in metals. **Table 1** below summarizes the various universities in Sweden and their main area of research and expertise.

Table 1 *Main field of research and equipment for AM of metals at universities and institutes in Sweden*

Universities		
University	**Equipment**	**Main field of research**
University West	PBF-EB & DED	process and material control
Chalmers	PBF-LB	materials and powders
Uppsala University	PBF-LB	materials, amorphous metals
Lund University	PBF-LB - planned 2017	design for metal AM, support material reduction, light-weighting, tooling
KTH Royal Institute of Technology	PBF-EB	production, materials
Linköping University	No metal	materials, mechanical properties
Örebro University	Available through collaboration	CT, CAD
Luleå Technical University	No metal	simulation, laser
MittUniversitetet	PBF-EB	medical
Stockholm University	PBF-LB	material properties
Karlstad University	PBF-LB - planned 2017	materials, tooling applications
Institutes		
Institute	**Equipment**	**Main field of research**
Swerea	PBF-EB, PBF-LB x2, Binder jetting (sand)	materials, process and production

Plans are underway for new equipment and activities at Karlstad University, and Lund University.

The research institutes in Sweden are also involved in research and development of metal AM in Sweden. The research institutes are focused on applied research in this field. For AM in metals Swerea has an extensive research program and has equipment for PBF-LB (both SLM Solutions and EOS, the latter in collaboration with Exmet), PBF-EB, and sand molds for casting of metals. RISE (formerly SP) runs projects around metal AM focused on medical industry, but does not hold any equipment for metal AM.

Centers have been built up around AM in metals where academy, institutes and industry are collaborating. The Swedish Arena for Additive Manufacturing of metals (AM-Arena) was started in 2016 by a collaboration between Swerea, Chalmers and University West. Today, the AM-Arena has around 20 members. Another center is Tillverkningstekniskt centrum (TTC) hosted at the Alfred Nobel Science Park. The center started in 2013 and today has 7 members (http://alfrednobelsp.se/3dtc/ [8]). More information about strategic investments in research in Sweden can be found in chapter 4.3.1.

3.1.2. Europe

Numerous universities in Europe are active in research related to metal AM. The majority of these universities are located in the UK, Germany and France. Though a full list is difficult to cover due to the rapid growth in this area, in
Table 2 below, selected universities and institutes are listed.

Table 2 *Examples of research areas and equipment for metal AM at selected universities and institutes in Europe*

University	Country	Example of equipment	Example of research area
University of Loughborough	UK	PBF-LB	Hybrid and multi-systems
University of Nottingham	UK	Binder jetting	System design, processes
University of Sheffield	UK	PBF-EB, PBF-LB	Powders and material
KU Leuven	Belgium	PBF-LB	Materials and process control
University of Erlangen Nurnberg	Germany	PBF-EB	Simulations and process development
RWTH Aachen	Germany	PBF-EB, PBF-LB	Productivity
INP Grenoble	France	PBF-EB	Materials development
Politecnico di Torino [9]	Italy	PBF-EB, PBF-LB	Materials
Institutes			
Institute	**County**	**Example of equipment**	**Example of research area**
Fraunhofer	Germany	PBF-EB, PBF-LB, DED	Materials, Technology, Quality
TWI [10]	UK	PBF-EB, PBF-LB, DED	Materials Characterization, Non-Destructive Testing
SIRRIS	Belgium	PBF-EB, PBF-LB, DED, Binder jetting	Design, Process

http://www.este.it/images/file-pdf/Uguesffto.pdf [9]

http://www.twiadditivemanufacturing.com/ [10]

In Europe, numerous centers have also been created to promote the collaboration between academy, institutes and industry. In Germany, one of the first centers that was created was the Direct Manufacturing Research Center (DMRC). This center is hosted by University of Paderborn and undertakes research in AM, both in metals, but also in other materials. In the metals research area, their focus is on laser melting, for materials and processing, construction and business. The center today consists of 22 partners, excluding the University of Paderborn.

Another large research center is the Manufacturing Technology Center in UK that was established in 2010. This center is not just focused on AM, but conducts research in numerous advanced manufacturing areas. The center was founded by TWI, the University of Birmingham, Loughborough University, and the University of Nottingham and today has more than 500 employees and around 100 members. More information about centers in Europe can be found in chapter 4.3.2.

3.1.3. USA

The USA is a large player in the field of metal AM, where extensive research in the field is ongoing and several US companies have taken metal AM into serial production. In the US, many Universities are involved in the field of AM and have been active since the early days of AM. However for AM in metal, it is not the usually named universities in the US that are the most active in this field. In the following **Table 3**, selected universities and research institutes in the US are listed. A number of larger universities that are active in research regarding AM are described at: http://www.sme.org/universities-involved-with-additive-manufacturing/ [11]. They are mainly from the US, but also from other countries.

Table 3 Example of research area and equipment for AM of metals at selected universities and institutes in the US

Universities		
University	**Example of equipment**	**Example of research area**
North Carolina State University	PBF-EB, PBF-LB	Materials development, medical devices
University of Texas El Paso	PBF-EB, PBF-LB	Process control, Material properties
Carnegie Mellon University	PBF-EB, DED	Simulation
Youngstown State University	Binder jetting	Material properties
Pennsylvania State University	PBF-LB, DED	Process
Institutes		
Institute	**Example of equipment**	**Example of research area**
Oak Ridge National Laboratory	I. PBF-EB, PBF-LB, DED, Binder jetting	Materials development, Materials charactersistics
National Institute of Standards and Technology	PBF-LB, Binder jetting	Standardization
Lawrence Livermore National Laboratory	PBF-LB	Materials Development, Certification

In the USA, a center for AM, America Makes, has been created as an initiative from the Obama Administration in 2012. More information about America Makes and other strategic investments in research in the USA can be found in chapter 4.3.3.

3.1.4. Asia

Research and development in metal AM in Asia is seeing a heavy increase. In 2015, 27% of all metal AM machines worldwide were sold to Asia, and principally to Japan and China. The Chinese government has put in extensive effort and funding into boosting research in the field of metal AM.

Universities conducting research in AM includes: Nanyang Technical University in Singapore that focuses on productivity for Singapore industry; the National University of Singapore that has a focus on biomedical research; Tohuku University in Japan is using PBF-EB to develop custom made alloys for biomedical applications. More information about research in Asia can be found in chapter 4.3.4.

3.1.5. Rest of the world

In other parts of the world, metal AM research has also been progressing. The following will give a few examples of other activities from around the rest of the world.

Centro de Tecnologia da Informação CTI is located in Campinas, Brazil and have activities mainly focused on biomedical applications. However, metal AM is an increasing focus and the institute holds both PBF-LB and PBF-EB equipment.

SENIA Joiniville, Brazil is a technical institute also located in Brazil. This institute has a focus on laser based metal AM and is partly government funded.

CSIRO, an Australian research institute is conducting research around metal AM for various industries. The institute offers a test bed for metal AM including PBF-LB, PBF-EB and cold spraying technologies for industrial usage.

3.2. Industry - current AM applications, drivers & challenges

3.2.1. Aerospace

The aerospace sector has found AM to be a suitable technique to use for their industry. The manufacturing of airplanes and aerospace components are, in relation to consumer goods and automotive, low series production. The manufactured components are usually complex and made in high end materials, such as titanium, high alloyed aluminum or super alloys, Today, the aerospace industry has come to the point of full scale serial production with AM for certain components, and the trend is that the number of parts and applications is steady increasing. Companies such as Airbus and GE are heavily investing in equipment to ramp up the production speed with ambitions of several thousands of machines in the 2020’s.

Current AM applications are mainly for low stressed “static parts” that are non-critical, and made out of traditional construction materials, such as Ti6Al4V and Inconel 718. However, official press releases from numerous aerospace companies have stated that more advanced AM parts will be used in the future. Another method of AM production in aerospace is by adding material to existing part in order to improve thickness, and thus increase strength. This enables prolonged use of parts as they can be repaired instead of scrapping them, and building completely new parts, thus streamlining production of aerospace components. Below are selected examples of AM used in the aerospace industry: http://www.gereports.com/post/80701924024/fit-to-print/ [12]

http://www.airbusgroup.com/int/en/story-overview/factory-of-the-future.html#chapter-05 [13]

- *GE Aviation* - Engine fuel nozzles for the Leap 1A engine is today a product that is in serial production in the GE AM manufacturing plant. Both the engine and the AM produced fuel nozzle are in full service operation on the Airbus A320 NEO family of aircraft operated by e.g. SAS and Lufthansa. Managed to lower cost, weight and number of parts with increased performance, the AM produced part has helped reduce fuel consumption in the engine. There are orders of more than 4500 engines.
- *GKN* - uses AM to add bosses on large static titanium castings using various DED processes. Components with these features are today in production and in flying service.
- *GE-Aviation* – The aero engine manufacturer has decided to produce 35% of the upcoming ATP engine by AM. The driver is to lower weight, increase performance, decrease number of parts to a lower cost. Is currently in development. https://www.geaviation.com/press-release/business-general-aviation/ge-tests-additive-manufactured-demonstrator-engine-advanced [14]
- *Airbus* – Today has full series production of non-critical parts to their families of commercial aircrafts. Tests are undergoing in also use the technology to produce critical parts. One example is a bulkhead wall that has a so called bionic design utilizing topology optimization to reduce weight, but maintaining the component strength. http://www.airbusgroup.com/int/en/story-overview/Pioneering-bionic-3D-printing.html [15]
- *Comac* - has in China teamed up with universities and a wing spar in titanium of up to 5 meters has been constructed. It was reported that AM was the method to be used to produce the wing spar for the Comac 919 commercial aircraft, which would then be the first ever commercial aircraft to utilize AM produced structural parts. http://www.3ders.org/articles/20130118-3-meter-long-titanium-airplane-part-3d-printed-in-one-piece.html [16]
- Honeywell – toady uses AM to produce Inconel parts for series production for aero engine components. Research is ongoing around other materials such as aluminum. https://www.honeywell.com/newsroom/news/2016/08/honeywells-additive-manufacturing-all-science-no-fiction [17]

Drivers:

- **Less material usage** - more near net-shape components means a reduced need for material (especially important for expensive materials such as Ni-based alloys and Ti-alloys)
- **Less post processing** - better net-shapes also means less machining and post-processing needed, and since machining is a significant cost for many aerospace components this enables cost savings
- **Shorter lead times** - enables manufacturing on demand rather than needing to keep warehouses filled with stocked forgings etc.

Challenges:

The main challenge is to fulfill the qualification requirements that are required by the aerospace industry for materials, process and production chain. Other challenges are:

- **Robustness and qualification of produced parts** – to achieve serial production of parts, there must be ways to guarantee that all AM produced components maintain the same quality.
- **Post processing** - for engineered surfaces on complex structures to maintain excellent fatigue properties efficient post processing methods must be developed to be able to refine the AM surfaces to maintain good fatigue properties.
- **NDT methods** – Efficient testing methods need to be developed that are suited for AM components in serial production.
- **Material properties** – are dependent on the processing routes and must be optimized for aerospace demands.
- **Increased production rates and robust process** – to be able to ramp up production rates, the machines must be faster to increase throughput of parts. The machines must also be able to guarantee uniform production regarding build speed, material properties and successful throughput.

Trends:

- Market trends are that a larger number of parts are to be AM-produced. Moving into more critical parts.
- New standards for AM processes as well as special AM materials are being developed. AM material is neither a forged nor a cast material but rather a new kind of material.
- "Design for AM" enables a new way of designing components, and this way of thinking is imperative in order for AM to become fully exploited.
- With increased experience, improved control systems, more robust AM processes, it will become possible to manufacture AM components for more stressed and loaded applications.

3.2.2. Automotive [18]

- Mostly prototyping with focus on plastic technologies
- Concept cars;
- AM as an integral tool in the design process

The automotive industry was one of the earliest adopters of AM technologies, beginning in the 90's, focusing on rapid prototyping and concept cars. Complex shaped jigs, tools and tool inserts can be printed economically. Printing of sand molds and cores for casting of metal parts are in use. Typical production of large volumes for majority of vehicle parts are too high to use AM economically for final parts. The only exception is in the gravity die casting process of complex casting parts, such as e.g. water jackets. This is running in full production of up to 100 000 parts per year at more than one European car maker. However, increased requirement for personalized or customized products has increased the interest to use AM also for final parts production. Currently, the motor vehicles sector corresponds to 13.8% of AM usage according to Wohlers Report 2016, being the third largest industrial sector benefiting from 3D-printing as series production. Wohlers report also states that the fastest growing technique in the automotive industry is binder jetting for printing sand cores and molds.

Passenger cars

- For several years, BMW has equipped their DTM racecars with water pump wheels made with AM. The 500th 3D-printed water pump wheel was fitted in April 2015. The high-precision component, which is subjected to high stresses, consists of an Al-alloy and has proven its worth in the tough environment of motorsports. Some small components for luxury cars (10,000 additively-manufactured parts integrated into series production of Rolls-Royce Phantom to date by BMW group by multi-jet fusion, design components, etc.)
- Ford. Currently AM metal parts are pumps and valves as well as cooling vents. Ford is casting cylinder heads, gearboxes, frame parts using 3D-printed molds and cores. All parts made in Al-alloys. Future 3d-printed metallic components can be engine components, body panel, suspension springs and OEM components. Mainly, Al- or Ti-alloys are expected to be used but also steel in certain components.
- HPD produced right and left exhaust manifolds, right and left rocker arm housings and oil filter housing in order to turn the V6 engines of normal cars (Honda Accord, Pilot and Odyssey) to a race car's engine.
- Koenigsegg has printed a turbo housing and parts in the exhaust system in metal for the new model One:1.
- Nissan Motorsports used AM to in-house fabricate a gurney flap (curved strip which extend off the rear trunk) to overcome aerodynamic challenges faced their Altima race car. Other parts were one-piece housings for the cooling system, a fan housing with integrated vane switch to control airflow inside the car.
- In 2016, Torsten Muller-Ötvös, CEO of Rolls Royce said the strategy for the company to survive is to use and implement new technologies like additive manufacturing. Almost all sold cars are customized where 3D scanning and 3D printing are used in manufacturing of prototypes. BMW, owner of Rolls Royce, has with start in 2012 tested 3D printed parts in the development of the new Phantom model. Most of the parts have been in plastic materials.

Sport cars

- Motor racing: lattice structure break disks, heat exchangers, components for the seats, etc. A complete racing car, Areion, has been 3D-printed by group T together with Materialise using SLA technique. AM was also used to optimize the cooling channels and to print nozzles and other parts in the cooling system.
- Blade – a super-light sports car with a 3D printed chassis. Divergent Microfactories provides a disruptive new approach to auto manufacturing that incorporates 3D printed aluminium joints, called a NODE™, connecting carbon fibre structural materials that results in an industrial strength chassis that can be assembled in a matter of minutes and thus build cars with a much lighter footprint.

Trucks and other heavy vehicles

- Mercedes-Benz 3D prints spare parts for trucks in order to reduce their physical inventory and also to be able to manufacture parts on demand.
- Renault Trucks developed a printing process for metals with the aim to improve the performance of the engines used in their trucks. The overall goal is a low weigh and compact engine. A prototype of a 4-cylinder engine was 3D-printed and it was possible to reduce the

number of parts in the engine with 25%, which corresponds to 200 parts with a total weight of 120 kg. Printed parts have successfully passed a 600 hours engine test.
- In Sweden Volvo is investing in AM especially in 3D-printing machines using binder jetting. They have several machines using these techniques for production purposes.

When replacing conventionally manufactured components with AM, in the vast majority of cases, they should be redesigned in order to add value from the benefits offered by AM. They could, for example, be redesigned so that it is possible to consolidate a number of subparts into one single component (**Figure 1**); or the component can be redesigned for significant weight reductions and/or performance improvements using topology optimization. However, due to the stringent requirements in the automotive industry, often only minor design changes are made, which may make the part "printable", rather than totally redesigning the component to really maximize the benefits that can be obtained from AM.

Figure 1 *Design for AM resulted in subpart elimination and weight reduction*

Figure 1 illustrates the benefits of a major redesign of a component, where part consolidation and optimized material selection have resulted in weight reduction of 61% (~1,4 kg) and reduced the number of subparts from 9 to 1. Further optimization would incorporate topology optimization and computational fluid dynamic simulation to further reduce the weight as well as optimize the functionality of the component.

Drivers:

- **Available materials** - more materials amenable for AM, improved AM-manufactured product quality and reduced post-processing.
- **Eco-efficiency** - The demand for producing more eco-efficient and lighter cars as well as the demand to produce new car models even faster than earlier are other drivers that suits a larger use of AM.
- **Spare parts** - It is important to have knowledge of the complete production chain from powder production via part production to recycling of worn out components.
- **Decreased development times** - Components with shorter design life, new models faster

Challenges:

- **Economics of AM limited to low-volume production** – the speed of the AM machines today are too slow to meet the throughput needs for the automotive industry,
- **Manufacturing large parts** – Today's machines, especially PBF machines are limited in build volume, which inhibits production of larger parts needed for the automotive industry.
- **Material price** – feed stock material costs are today too high to be economically advantageous.
- **Availability and reliable material data** – The materials behavior differs from conventional manufactured materials, and secure material data must be available.
- **Talent shortage** – There is, today, a lack of knowledge in AM in engineers. Expertise in the area is also limited in Sweden.
- **IPR concerns** – New types of IPR questions are raised because of the use of AM, and easier ways of reverse engineering.

3.2.3. Engineering/manufacturing

This industry segment includes both direct use of AM in producing final and functional parts, but it also cover indirect use of AM in the manufacturing process. Indirect AM can be processes like printing of molds and patterns for casting or tools and molds for use in stamping and injection molding processes. According to Roland Berger [19] the manufacturing of tooling by metal AM has in 2015 reached a TRL-level of 9, meaning the development has reached accepted manufacturing levels.

Numerous examples can be found where this industry segment is active in pursuing production with AM in metals. Examples are tooling for sheet metal forming [20] [21], robot grippers, jigs and fixtures [22], patterns for sand casting, for welding and assembly [23].

In Sweden the TRL is usually low, and focus is on case studies and prototyping for "direct to use parts". However, the following examples have been reported:

- **Sandvik AB -** has earlier announced the creation of a new R&D Center within AM. The center has the objectives to investigate potential business for metal AM within Sandvik AB. The center is now part of a new business area for AM within AB Sandvik Materials Solutions.
- **VBN Components –** a Swedish company that has proven the possibility to use state-of-the-art materials and AM processes to produce highly wear resistant cutting tools, see **Figure 2**.
- **Tetra Pak –** has investigated the possibility to use AM in their processes by using a 17-4PH additively manufactured induction sealer.
- X**ylem Wastewater (former ITT Flygt**) – purchased its first printer in 1987 for prototyping and invested in a sand printer from EOS in 1997 to print molds and cores for spare parts to their drainable pumps. Now they are going to invest in a printer from ExOne.

Figure 2 *Milling cutter for gear manufacturing. The cutter is produced using AM in the material Vibenite®280, high alloyed HSS steel with an iron base, with a large number of carbides evenly distributed in the metallic matrix. Curtesy: VBN Components*

Drivers:

- **Components with potential for customization** – components can easily be customized for each user or for the specific application.
- **Components with shorter design life/new models faster** – the constant shortening of life time for products require products to come to market faster. AM can be used for both prototyping activities, as well as for more flexible production.
- **Lightweight possibilities** – new design possibilities make it possible to make components with lower weight, but maintain structural properties.
- **Internal channels/structures** – new design possibilities make it possible to produce components with i.e. asymmetrical cooling channels closer to the working area.
- **Functional part consolidation** - new design possibilities make it possible to integrate numerous parts that formerly required assembly to be produced as only one part.
- **Designed surface structures or specific material options** - are good candidates for AM and can improve component performance

Challenges

- **Processing Speed** – today AM is too low to compete with traditional manufacturing
- **Process Robustness** – for serial production with numerous machines, this must be understood
- **Quality assurance** – Easy ways to ensure good quality products
- **Cost** – AM is today a costly process compared to traditional ones, especially powder materials
- **Knowledge of design for AM to use its full potential** - Understanding on when and how to use AM rather than traditional manufacturing, and how to design to maximize its value

3.2.4. Medical & Dental

The medical and dental sector is the fifth largest sector using additive manufacturing with about 12.2% [23] of usage. In the medical sector, applications of AM have today reached large-scale industrial manufacturing. Numerous applications in both polymers and metals are being used for standard as well as customized products.

In a global perspective, there are a number of strong market segments where additive manufacturing have established a strong basis and become a major/sole manufacturing technology. These segments includes: instrumentation (guides for assisting cutting and drilling guides during surgeries, special instruments, etc.); implants (standard implants as e.g. hip joints and dental implants, customized implants, etc.); external prostheses (e.g., hands, hearing shells, etc.). AM saw a rapid development in the hearing aid industry starting from 2007/2008. Today about 99% of the hearing aid shells, that are customized for each patient, are produced by AM

The dental sector is one of the most developed sectors that have recently adopted AM. The applications include splints, drilling guides, impression trays, crowns, bridges, specialized tolls, etc. The global market is concentrated in the hands of the big players, e.g. Danaher, Densply-Sirona, Zimmer Biomet, 3M, Align Technologies, Bego, etc. SMEs are currently the flexible adopters of AM for the dental industry, focusing mostly on the manufacturing of crowns and bridges as a part of the supply chain to the dentists. Examples from Swedish industry include:

- *Wiema AB* - (former Dentware Scandinavia AB) with headquarters in Helsingborg uses PBF-EB and PBF-LB to offer customized dental crowns and bridges in titanium and cobaltchrome alloys.
- *3D Tech Sweden AB* - is a newly founded company which is using PBF-LB processing methods to manufacture customized dental replacements.
- *M-Tec Dental AB* - is another company in the same business area and they have two Concept Laser machines for PBF-LB.

For standard implants, AM is mostly developed for production of orthopedic implants. Examples of activities include:

- *Stryker* - is one of the largest users of AM to produce standard as well as customized implants. The focus areas are medical and surgical (surgical equipment, etc.), reconstructive (hip, knee, foot and ankle implants, etc.,) and neurotechnology and spine (spinal and craniomaxillofacial implants, etc.).
- *DiSanto* - is another US-based company that is a part of Arcam Group that utilizes PBF-EB technology for manufacturing of the orthopedic implants.
- *LIMA Corporate* - uses PBF-EB to manufacture acetabular cups for hip replacements. The acetabular cups use a 3D designed lattice structure to promote bone ingrowth and former anchorage of the implant. Today several machines are in serial production of such implants and LIMA today holds 3% of the world market.
- AIM Sweden AB - in Sweden is a SME with focus on customized implants manufactured by PBF-EB.
- OSSDsign - produces customized cranial implants using parts made from additive manufacturing supplied by subcontractors.

- *Ortoma AB* – is focusing on development of the integrated surgical systems with application of AM.

Additive manufacturing is also widely used for manufacturing of models for educational purposes as well as pre-operative bone models that are used for training before operation as well as support during operation.

- *Sahlgrenska University Hospital, Uppsala University Hospital and Karolinska University Hospital* - are performing surgeries utilizing customized implants as e.g. maxillofacial recovery. However, today only a couple of dozens such surgeries are taking place with implants typically manufactured by SMEs outside Sweden (UK and Netherlands).

Drivers:

- **Possibility for easy mass customization** – implants and other medical parts can easily be customized for each individual patient.
- **Material savings during manufacturing**– in medical devises, often high end materials are used. With AM material is only put where needed.
- **Small sized production** – Batches of one are easy to produce. Also, several individual components can simultaneously be produced.
- **New geometries possibilities** - e.g. acetabular designed structure on hip implants where the 3D-lattice structure is optimized for bone ingrowth

Challenges:

- **Certification and medical approvals for customized implants** - medical devices must be certified by e.g. FDA in the US for use in patients. This certification can be challenging when customizing each product for the individual patient.
- **Biocompatible materials focused for medical applications** – materials used for biomedical applications must be biocompatible to use. Also surface chemistry must be tailored for biocompatibility.
- **Quality control** - fast and easy quality control must be done for implants.
- **Geometry assurance and resolution** – Tolerances in the medical devices industry are tight and surface morphology is important for the implant to be well integrated with the body. For dental, the resolution of the process must be high to meet the tight tolerances.
- **Efficient post processing of customized parts** - every product is different, and the post processing methods needs to be able to perform finishing in a flexible way for the process chain to be efficient.

3.2.5. Consumer products

Consumer products and electronics cover about 13% of AM applications when comparing various application sectors (Wohlers report 2016 [23]). The fashion sector is very active because AM gives new ideas to designers, but they are also pushing the boundaries of AM by creating fabric-like prints of more comfortable materials, as well as with jewelry by using indirect methods, i.e., 3D-printed molds and casting. Home and office decoration, personal accessories, and toys are other examples of growing application areas. The jewelry industry is increasingly using AM for the production of complex shapes and geometric features in precious metals.

Examples of applications include:

- Cookson Precious Metals (CPM) and EOS have co-developed the precious M 080 system for jewelry and watch-making industries. It can be used for volume production of parts in 18k yellow gold. Cookson also offers other gold grades as well as silver, platinum and palladium. It enables individual specimens and customized serial products to be manufactured cost-efficiently. The jewelry manufacturing technique for gold was first developed by Towe Norlén and Lena Thorsson and the company Particular AB (2004-2007) in Sweden [24], [25].

- Frank Cooper, School of Jewelry, Birmingham City Univ., UK says that sintering with AM is the new paradigm for the jewelry manufacturer and that the European jewelry industry is poised to develop potential of direct metal laser melting in precious metals [26].

Figure 3 *The jewelry shown above, size 50 x 25 millimetres, was worn by Bahar Pars, one of the leading actresses in the nominated film "En man som heter Ove", at The Oscars 2017 held in Hollywood on February 26, 2017. The jewelry is designed by Naim Josefi and is printed in Swedish tool steel at 3D Metprint, Älmhult using their 3D Systems ProX300 metal printer.*

Figure 4 *Monfort Strata, a crowd funded wristwatch with unusual features: a scratch-resistant, hardened steel case and a textured 3D printed dial. Made of stainless steel, the dial is made by binder jetting by Digital Metal to create a relief surface named les massifs, the motif is inspired by the Swiss Alps. With a repeating triangle pattern, the dial resembles the crystalline structure of rock, and is a visual variation of the traditional hobnail, or clous de Paris, guilloche. (www.monfortwatches.com [27])*

Figure 5 *Höganäs jar, originally made in in salt glazed stone ware, now printed in metal by binder jetting by Digital Metal. One is as-sintered and one super finished with the height of 21.3 mm.*

- Other examples are design interior products like 3D-printed DXV luxury bathroom faucets available from American Standard or 3D-printed door handles, for example, the "Machine Vision" door handle designed by A. Pelikan.

Drivers:

- Creating complex structures which are difficult to produce by other methods together with personalization.

- Enables individual specimens and customized serial products to be manufactured cost-efficiently
- The availability of tool-less fabrication will influence what is designed, how it is designed, and the quantity of products offered
- Innovative design could be considered vital for the survival of the high-value-added industries like jewelry manufacturing

Challenges:

- Optimization of raw materials as well as manufacturing processes for printing easily vaporizable metals using laser based processes
- Jewelry industry designers and manufacturers need to become aware very quickly of how unsettling and disruptive this technology introduction has the potential to become
- New jurisdictional and technological solutions must be implemented to ensure that the IP right of designers are protected

3.2.6. Electronics

Consumer products and electronics cover about 13 % of applications when comparing various application sectors (Wohlers Report 2016 [23]). It is of the same order of size as the aerospace, motor vehicles, medical/dental and industrial business machines.

While NASA explores the power of 3D printing in the development of the next generation space exploration vehicle, a CubeSat Trailblazer was launched in November 2013 that integrated 3D-printed structures with embedded electronics. Space provides a harsh environment necessary to demonstrate the durability of 3D-printed devices with radiation, extreme thermal cycling, and low pressure—all assaulting the structure at the atomic to macro scales. Research has begun to focus on more sophisticated systems with process interruption capabilities including (i) inserting components (electronics, magnetic, sensors, batteries, etc.) into specific cavities within fabricated structures, (ii) dispensing widely disparate materials for specific functionalities (thermal and electrical conductivity, radiation shielding, optics, flame retardance, etc.), and (iii) embedding solid conductors within polymer substrates through the use of ultrasonic or thermal energy in order to provide high performance electrical interconnect. Integrated together these technologies are able to 3D print multifunctionality to produce complex functional electronic and electromechanical systems in an automated manner [28].

Therefore, it is not surprisingly that statements as follows appear:

- Jeff DeGrange, Stratasys: "Bringing together 3D printing and printed electronic circuitry will be a game changer for design and manufacturing. It has the potential to completely streamline production by requiring fewer materials and steps to bring a product to the market".
- Optomec: "Printing electronic components directly on or inside the physical device eliminates the need for separate printed circuit boards, cabling and wiring thereby reducing weight and size while also simplifying the assemble process".

- Guardian: "3D printing could revolutionize the solar energy industry. More efficient, less complex and cheaper 3D solar cells can also capture more sunlight than conventional PV models".

Below a few examples to illustrate the use of AM in the electronic industry [29]:

- Voxel 8 in partnership with Autodesk (www.voxel8.co [30]) presented world´s first 3D electronics printer with 2 jetting heads; one FDM for plastics and a second head for conductive pastes.
- Nano Dimension's DragonFly 2020 3D printer is a highly accurate and versatile inkjet deposition and curing system for printing professional multilayer circuit boards. The printer inkjets high-conductive nano-silver inks on a 20 x 20 cm circuit board and it is also possible to print dielectric inks. (www.nano-di.com [31])
- The thermal resistance of a heat sink was dramatically reduced through an additive design iteration process [32].
- NextFactory – Hybrid System, http://nextfactory-project.eu [33] an EU funded project 2013-2017 with the aim to develop a Hybrid System in One machine involving 3D printing (packaging) using Functional/Smart materials for Functional components (sensor systems etc.) together with 3D assembly and Inspection & testing, all in one machine.
- Optisys has used PBF-LB to disrupt the antenna design and manufacturing market for high level integration and customization of microwave waveguide components such as waveguide arrays, monopulse antennas and comparators, cooling structures, waveguides and connectors.
- Other examples are lightweight X-band band pass filter (polymer and then metalized), metallic horn antennas (PBF-LB of 316L) for millimeter and sub-millimeter wave applications, 60 GHz integrated lens antennas (SLA of ceramics) and horn antenna with embedded coaxial transition (ABS).

Drivers:

- 3D-Printing builds 3D objects with integrated electronics
- Multiple materials: conductive and non-conductive
- Embedded components into 3D parts during 3D-printing
- The future - A hybrid system – 3D-printing + printed electronics?

Challenge:

- Cost of equipment and materials
- Today limited to Ag and Cu inks. Tomorrow Graphene?
- Design tool/modelling challenges, for example, new failure models for 3D-printed structures
- Quality and reliability – can we meet the specifications?
- Surface roughness since its influence on loss is problematic to simulate.

3.2.7. Energy

Among the various envisioned applications of AM, the Energy Sector occupies a prominent position. Wide-ranging use of AM, spanning (a) prototyping, (b) manufacture, and (c) repair, is foreseen in virtually all types of energy generation. For example, turbines and turbos have always been complex to produce and are preferred to be as light as possible, thereby making them ideal AM candidates. Similarly, on site repair is a particularly attractive proposition for oil & gas services. Manufacture of small modular reactor (SMR) components for nuclear energy production are also considered interesting and are already being actively pursued. As mentioned later in this report, solar energy, fuel cell and other renewable energy applications are also attracting attention. In realization of the above, AM is now an important constituent of US Department of Energy's Clean Energy Manufacturing Initiative.

The TRL levels of processes being developed, evaluated or already adopted for varied applications in the Energy Sector are challenging to ascertain because of limited information being available in the open domain and the understandable approach of the industries to be guarded even in revealing "success stories" so as to stay ahead of the competition. Nevertheless, it is clear that several parts are already in production. These include several examples:

- Siemens - rapid manufacture of swirlers and burner heads. Rapid repair of burner tips and rapid prototyping of turbine blades are also being carried out at Siemens' Finspång facility in Sweden is anticipated.
- *GE Oil & Gas* - already has a completely automated line in Talamona, Italy to AM produce end burners for gas turbine combustion chambers [34] [35].

Clearly, the above examples are only illustrative and intended to convey that the AM techniques have vast potential, and that the industry is also keen to embrace them. However, many countries have begun to advocate and create suitable environments for public-private partnerships and multi-agency collaborations, which are considered crucial to make intelligent use of resources and expertise for ensuring faster progress up the TRL ladder to catalyze widespread adoption of AM.

Drivers

The rapidly growing interest in the Energy Sector to evaluate and adopt AM for meeting various application needs stems from the industry's appreciation of the numerous incentives that the approach provides. Some key perceived benefits that presently drive the interest in AM are listed below:

- No geometry restrictions while designing can yield unique benefits
- More internal cooling options in turbine hot gas paths
- Architecture simplification, integrated assemblies for easier part installation
- Performance gain
- Produce parts for repair or refurbishment "on demand" instead of stocking large numbers of legacy parts for customers

The specific drivers indicated above are also supplemented by the following somewhat generic anticipated gains applicable to several other/all application segments:

- Rapid manufacture and reduced resources, leading to cost reduction
- Freedom-of-design possibilities
- Quick upgradation to new component designs and rapid product introduction

- Environmentally sustainable – reduced emissions; lower environmental "burden" compared to conventional processes

Challenges

Regardless of the numerous benefits that motivate adoption of AM processes, it is also becoming increasingly apparent that several key challenges will need to be surmounted if these technologies are to live up to their full potential.

- **Extensive testing, data collection and demos** - are needed to enhance the level of confidence among user industries, particularly when structural integrity of the built component is a crucial property requirement. Demonstrating the feasibility of reliably producing builds involving heterogeneous material systems, both functionally graded as well as in discrete hybrid form, will also widen the applicability of AM.
- **Tailoring of critical surfaces** - by using a material distinct from that used for building the bulk component will be most relevant, as we look toward future applications that can involve production of components that operate in aggressive environments and, consequently, need to be protected from surface degradation. This will be akin to *in situ* surface modification of parts.
- **Expand the range of materials that can be 'built' using AM techniques** - this material spectrum has to grow if the rapid product introduction benefit of AM is not to be offset by the long time required to optimize process parameters for a new material grade. Simultaneously, it would also be judicious for the user industries to actively participate in proactively designing energy system components to take full advantage of AM capabilities.

As in case of the drivers, several other challenges also loom on the horizon that can be deemed common to realization of AM applications in general.

- **Need for standards** - to encourage broader adoption
- **Development of suitable sensors** - to enable reliable process monitoring and control
- **Tolerances and surface finish** - of built parts is also a matter of continued concern.
- **Ensure efficient supply chain** - is also essential for cost competitiveness from a commercial standpoint.

Market Trend

Components of Ni-based superalloys, Ti alloys, Co-Cr-Mo compositions, various types of stainless steels, maraging steels and several other special materials have already been built using AM for varied energy applications. Among them, Alloys 718 and 625 constitute the most frequently used superalloys, along with Hastelloy X. Convinced that AM is poised to add an entirely new dimension to meeting their future manufacturing needs, both GE (USD 1.5 billion during 2010-16) [34] and Siemens (Euros 21.4 million) [36] have invested hugely in AM infrastructure.

It is also encouraging to see new grounds being incessantly broken from the standpoint of utilizing AM for energy applications, with different AM techniques being explored for (i) creating molds for wind turbine blades [37] (ii) fine-feature collector lines on solar cells [38] (iii) material deposition on non-planar supports for producing cylindrical-type SOFCs or ceramic membranes [38] (iv) metallic bipolar plates in PEM fuel cell stacks [39] [40]. The Caterpillar company, Solar Turbines already builds their fuel swirler by AM. Trials by Westinghouse to adopt AM for nuclear energy applications has shown impressive reduction in build times (up to 75%) and costs (up to 50%) [41]. Siemens has successfully tested its additively manufactured gas turbine blades. The full load testing of Ni based super alloy blades at speeds reaching 1600Km/hr and temperature at 1250 ^{0}C is considered a groundbreaking success in the power generation sector [42] . Siemens engagement in printing parts for nuclear power plants is also worth mentioning; in this initiative, an old metallic impeller of a fire protection pump is replaced with a reversed engineered 3D printed component and installed for operation in Slovenia's Krško Nuclear Power Plant [43]. Interest is also emerging in utilizing "hybrid additive-subtractive manufacturing" to harness the advantages of each, as they both support as well as complement each other. e.g., add features of a hard metal by AM onto a shaft made of some other material by SM. This will become particularly relevant when industries begin to more actively adopt the "design for AM" approach.

3.2.8. Machine suppliers

Sweden has two manufacturers of AM systems in Arcam (PBF-EB) and Digital Metal (Binder Jetting).

- Arcam's business strategy is focused on orthopedic and aerospace applications. While it is possible to process many materials with the PBF-EB machines, the primary emphasis is on titanium and cobalt-chrome [23]. As of today, Arcam is alone in commercially supplying PBF-EB machines.
- Digital Metal AB is part of Höganäs and produces binder jetting equipment. However, machines are not sold to other companies [23]. Today, Digital Metal predominantly produces parts or components in stainless steel. However, other materials such as titanium, silver and copper are close to commercialization [44].
- A very relevant type of post treatment of AM produced parts is Hot Isostatic Pressing (HIP) where Quintus Technologies, situated in Västerås, Sweden is a world leader in high pressure technology and supplier of HIP units [45].

Besides PBF-EB, there are several international manufacturers that can supply LS machines.

- Among the suppliers are EOS, SLM Solutions, Concept Laser, 3D System (Phenix), Renishaw, Realizer, Trumpf.
- In the field of Directed Energy Deposition (DED), companies such as Trumpf, Optomec, BeAM, Accufusion, Irepa Laser, Hybrid Manufacturing Technologies (laser), and Sciaky (EB) are supplying machines.
- International suppliers of Binder Jetting equipment are ExOne and Voxeljet.
- Hybrid machines are supplied by DMG MORI, Mazak, and Matsuura.
- XJet and Vader Systems are suppliers of Metal Jetting systems.
- Equipment for Sheet lamination is provided by Fabrisonic, a joint venture between Solidica and EWI.

In

Figure 6, the market share based on sold units up to 2016 can be seen.

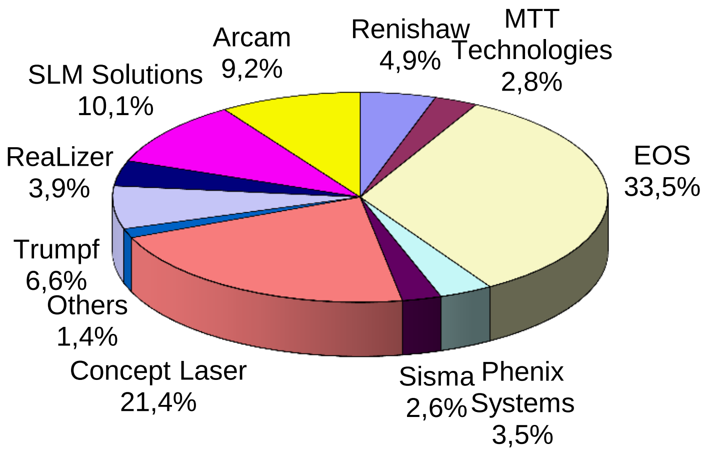

Figure 6 The market share based on sold PBF units up to 2016, from Wohlers Report 2017 [23].

Drivers:

- **Increasing use** – AM is currently gaining a lot of attention and usage is steadily increasing.
- **Better machines** – machines and their capabilities are currently undergoing rapid development.
- **Industrial use** – AM is going from being a technology for prototyping, to being a technology for industrial production.

Challenges:

- **Meet demands** – as AM is gaining acceptance in various industry segments, it is important for the machines supplier to continue the development of their systems to meet the increasing needs, both in performance and number of units.
- **Manufacturing speed** – for PBF machine suppliers, there is a great demand for increased production speed for the process to become economically viable in an increased number of industry segments.
- **Manufacturing size** – today, for certain industries there is a great need to able to produce even larger components in PBF machines. Examples are the aerospace, energy and automotive sectors.
- **Available materials** – the number of alloys that are available to the various machines are very limited. Also, the development of a new material is a tedious and expensive process with trial and error work to make the new material work. For AM to be more extensively used, a larger number of materials and material suppliers are needed.
- **Process monitoring and robustness** – AM machines have, until recently, not been equipped with any process monitoring or feedback loop capabilities. Today, efforts are undergoing to start monitoring the processes, especially for defect determination. However, a feedback loop for process stability and process recovery is still needed.
- **Industrialization** – the machines must become easier to use, and with a decreased need for manual labor in preparing and reloading of the machine as well as in post-processing. The complete machine systems must be designed to fit into a production environment.

3.2.9. Material suppliers

The five main metal powder producers in Sweden are Carpenter Powder Products, Erasteel, Höganäs, Sandvik and Uddeholm. Metasphere in Luleå is an SME developing their own process for plasma atomization resulting in very spherical metal powders that could be suitable for AM.

Carpenter produce gas atomized powder in Sweden and the US. Large quantities of the powder produced in the US goes to aerospace applications. Materials that need vacuum melting or argon atomization are not produced in Sweden where more general, industrial applications are targeted. Carpenter quite recently acquired American titanium powder producer Puris LLC.

Erasteel produces VIM (Vacuum Induction Melting) gas atomized fine powder for e.g. AM, under the brand name Pearl® Micro. A variety of Ni-base alloys, Co-base alloys, stainless steels, tool steels and high speed steels are supplied for AM [46] [47].

Höganäs's main powder production in Sweden is water atomized powder of various steel alloys. The water atomized powder is mainly used for sintering and pressing applications in various industries. However, Höganäs also produces powder specially designed for AM in the materials of stainless steels, tools steels, Nickel alloys and cobalt alloys [48].

Sandvik produces powder for AM applications covering material types such as stainless steels, Co-alloys, Ni-alloys, tool steels, maraging steels, low alloys steels and Cu and Cu-alloys. Most of the powders are produced at Sandvik Osprey in UK, but VIM gas atomized powders are also produced in Sandviken [49].

Uddeholm is a producer of advanced tool steels for various applications. The company is currently intending to move into the AM market and offer their products for metal AM application with a launch of the first powder planned to 2017. Uddeholm intend to produce powder for specific tooling applications [50].

A few selected non-Swedish powder producers for AM include HC Starck, AP&C and TLS Technik. HC Starck is a German material supplier that, among other things, produces atomized metal powders and alloys under the brand name AMPERSINT®. E.g. stainless steel, Ni-base and Co-base powder is produced for all AM processes [51]. The Canadian company AP&C produces titanium powder by plasma atomization. AP&C was acquired by Arcam in 2014 [52]. TLS Technik is a German company that, through the EIGA process (Electrode Induction-melting Gas Atomization), produces powder from reactive and high melting metals and alloys such as Zr and Ti alloys [53]. There are also non-producers selling AM powder, one of which is LPW, offering a wide variety of powder types [54]. Most AM machine suppliers also supply powder for their own process without producing the powder themselves. Italian end user Avio Aero, part of GE, has invested in its own powder manufacturing facility.

The available manufacturers, and the amount of different alloys, of wire feedstock for directed energy deposition (DED) is greater compared to powders. This is because of the fact that the wire feedstock for welding can also be used for DED. There are a number of manufacturers in Sweden that produce wire feedstock for welding/DED such as (CE approval):
AVESTA WELDING (http://www.voestalpine.com/welding/se), ELGA (http://www.elga.se/),
BÖHLER (http://www.voestalpine.com/welding/se), ESAB (http://www.esab.se/),
FILARC (http://www.esab.se/), LINCOLN ELECTRIC (http://www.svetskompaniet.se/),

SANDVIK (http://www.smt.sandvik.com/), NITTETSU (Norway, http://nst.no/),
UTP (http://www.voestalpine.com/welding/se).

The aforementioned manufacturers are strong in various steel grades but, in the area of aerospace materials, the USA still currently possesses the largest market share. But countries such as China and Russia are trying hard to increase their share of this market.

Drivers:

- **New markets for powders and wires** – since AM is a user of powders and wires as feedstock material, the market for the supplier of these feedstock can move in to new markets as AM, and its use of materials, increases.
- **New materials needs** – today, only a limited number of metallic materials are commercially available. The materials used today are also focused on materials developed for conventional manufacturing, whereas materials customized for AM can open up new possibilities
- **Increased volumes** – as AM continues to gain trust as a production methodology, the amount of powders and wire feedstock will increase.

Challenges

- **Optimize the material properties for the various AM processes** – powders for AM differ in their requirement from conventional powder and wire manufacturing processes. Properties such as i.e. sphericity and chemical compositions must be tailored for AM use.
- **Proper analysis** - of powder properties such as powder flowability and spreadability must be developed to meet the specific needs for AM.
- **Make the powders suitable for the AM processes** - Today, machine suppliers only offer their own powder with validated process parameters to their customers. For traditional material suppliers to be able to deliver feedstock material is a challenge that must be met.

3.2.10. Software suppliers

Software is, of course, a key component of the whole AM development - production chain. AM is, by its definition, digital: building layer upon layer from a digital design.

Design: In design, topology optimization of the built component is a growing area of interest for AM. AM technology is perfect for topology optimized designs because it is possible to build such designs that may not have been previously possible to manufacture. Basically all finite element analysis tools can be extended with respective AM optimization tools. A list of some tools can be found at: http://www.topology-opt.com/software-list/. There are also some free licensed tools available. (GPL and similar licenses)

Production preparation: Every machine has its own control software (PLC) defining some of the machine specific build features needed to run the machine. Other parameters, such as design and material specific parameters, must be supplied to the machine via a software interface. For powder bed technologies there are tools for the preparation of the CAD file to suit the AM machine. All machines need different setups and dedicated input-formats to function. In production planning the tools make it easy to add support structures, rotate the component according to build standards,

place one or several component in the chamber, standard compensation for shrinkage, etc. Such software packages include:
Magics by Materialise: By far most used tool for AM file preparation
Siemens NX just recently hit the market. NX covers basically the whole AM chain

For robotized AM, the preparation phase today is basically manual, and programming the robot paths is done with the software shipped with the robot.

Simulation of the build process: There are several reasons to simulate and model the AM build process. The main reasons are i) to capture the shape distortion in the building of a component so geometric adjustments can be done in advance ii) to identify the residual stress states in the component which can be disastrous to its load carrying capacity iii) to improve the building sequence and/or energy deposition in order to improve the quality of the component.

Several actors on the market have realized the potential in dedicated AM simulation software. Today there only exists a handful commercial software packages that have these AM modelling capabilities (They are either dedicated to AM simulation, or have an AM simulation module added to general purpose FE-software). Some examples include:

- Virfac by GeonX (Belgium),
- Amphyon by Additive Works GmbH (Germany),
- exaSIM by 3DSIM LLC (US)
- Project Pan by Autodesk (US).
- Simufact by MSC (US)
- Simcenter, by Siemens (Germany)

Dassault Simulia, developer of Abaqus, is working on an AM module, possibly available in their 2017 release. In academia Abaqus, Comsol, Sysweld and ANSYS are popular choices because of their relative openness to user tweaking. There also exists one open (GPLv3) package for simulation of the distortion in the building of the component. It is most applicable to powder bed processes.

- FAME: (Free Additive Manufacturing Enhancer) uses the CalculiX non-linear FE-code as backbone. Found at https://github.com/swerea/FAME.git

Coupling to higher order control systems. Additive manufacturing is a very young production method and is, in fact, today relatively little used in factory environments. That means that they do not yet have generic tools for connecting to MES (Manufacturing Execution System) and further up to the ERP (Enterprise Resource Planning) systems.

3.2.11. Component manufacturers

Several component manufacturers, also called service bureaus, for AM in metal have been established in Sweden over the last few years. The bureaus cover a wide range of available processes and materials and are located throughout the country. Several Swedish service bureaus dedicated to in-house component manufacturing and prototype manufacturing in metals have been commercially established. These include:

- **Lasertech** – based in Karlskoga and offers multiple technologies such as PBF-LB, PBF-EB and DED. http://www.lasertech.se/se/3d-printing

- **Höganäs Digital Metal** – a subsidiary to the Höganäs Corporation located in Höganäs. The company offers parts produced by a technology developed in house which is based on binder jetting in metal. https://www.hoganas.com/3dprinting/
- **AIM Sweden –** situated in Östersund and is focused in PBF-EB manufacturing of metallic components. http://aimsweden.com/
- **3DMetPrint** – uses a powder bed technology from 3Dsystems to print metallic components and is based in Älmhult. https://www.3dmetprint.com/
- **Digital Mechanics** - offers this service, but do not have any manufacturing in-house and use suppliers for that service. http://digitalmechanics.se/snabb-produktion/
- **Sandvik Machining Solutions –** the AM-center manufactures components both for internal and external customers.

Drivers

- **AM is a new technology -** The metal-AM process today requires much hands on experience that is not always available at companies.
- **Large investment –** The investment in a metal-AM system is high. Service bureaus are an alternative to own investment.
- **Fast production –** Due to not requiring tooling and its digital way of working, AM processes have great potential for service providers as product changes can be fast.
- **Production flexibility -** The service bureau itself has the possibility to be flexible in its production. For the client, the service providers provide a way to fast and flexible part production.

Challenges

- **Lack of knowledge -** Usually, these service providers need to spend time to inform their clients what the possibilities and limitations are with metal AM and to teach them how to think about using AM.
- **Lack of available materials –** Customers are constantly requesting specific materials for their application.
- **Lack standardization for certification purposes** – The service bureaus needs to adapt to the clients specific needs. Especially for part production which require standards and documentation.

3.2.12. Other and SMEs

In Sweden, a number of SMEs involved in metal AM from various aspects have been identified and presented here:

VBN Components – is described in section 3.2.3-

Exmet - is developing amorphous metal components using AM. Due to the spot like melting, the AM processes beneficial for producing so called metal glass. The company is still in the development phase of the process, but is expected to produce prototypes in 2016. Together with the Hereaus Group, Exmet is developing materials and processes [55] [56].

Freemelt – is a startup in an early stage and has the objective to build open source electron beam based powder bed systems aimed for research and development purposes. The team has genuine experience in the electron beam technology [57].

3D-Tech Sweden – started in 2016 and is using AM technologies in metal to produce products for the dental industry. The company also offers services for orthopedic and industry applications [58].

3.3. Society

The project to write a road-map for research and innovation to industrialize additive manufacturing of metals in Sweden has been commissioned by the strategic innovation program Metallic Materials and financed by Vinnova. The roadmap is also of interest for the strategic innovation programs such as Lightweight, Production 2030 and Innovair. Though funding for research in AM of metals has been given over the last few years for different projects, the overall strategy and goal are still missing. The funding agencies already supporting projects within this area are e.g. Vinnova, the Swedish Foundation for Strategic Research (SSF), the Knowledge Foundation (KK-stiftelsen), the Swedish Agency for Economic and Regional Growth, ÅFORSK and the Swedish energy agency. Furthermore, AM of metals is also an interesting area for the Swedish research council Formas and the Swedish national space board.

Another important AM stakeholder is the government, especially through the Ministry of Enterprise and Innovation, Ministry of defence (FMV, FOI), Ministry of Education and Research and Ministry of the Environment and Energy. AM has been highlighted in the government’s strategic innovation partnership programme “A connected industry and new materials” as one focus area. The aim is to find innovative solutions to many of today's major societal challenges.

4. Key initiatives

4.1. Strategic alliances, networks, knowledge centers, competence platforms

Throughout Europe, strategic alliances have been formed between universities and research institutes and industrial partners and they have joined in various EU funded projects. Many of the strategic alliances in Europe were formed during the 7th framework programme for research, FP7. Such competence and knowledge centers include, for example, DMRC, LaserZentrum Nord, CRC 814 and EPSRC Centre.

In the USA, AM has generated a number of collaboration platforms to promote different types of research. Unlike most of Europe, where we have research institutes as the link between basic research at universities and R&D in industry, these represent a new way for the American industry to develop and implement new technologies. One of the more familiar such knowledge centers is NAMII, also called America Makes.

Further information about different alliances, networks and competence centers etc. can be found in the different roadmaps and studies in **Appendix 1** and in chapter 4.3.

4.2. Company acquisitions

Business for machine builders has recently taken off after years of struggling with profitability and slow market penetration. Most of the companies were privately owned for a long time but, in 2013, many of the companies were registered on the stock market. Since then, company mergers and acquisitions have increased with a boom with 3D Systems and Stratasys, in 2016 and 2017, being the most aggressive buyers. A list of different mergers and acquisitions since 2013 can be found in **Appendix 2.** One of the most recent acquisitions with an impact on Sweden was GE acquiring a majority share in Arcam AB.

4.3. Strategic investments in AM research

Although AM isn't on the hype curve any longer there is still a good interest from industry to consolidate and create partnership or buy strategic companies. Finding the total of all investments in AM is not easy, as investment in AM equipment is not cleanly divided between manufacturing and research. In **Appendix 3** figures from Wohlers report 2016 [23] show investments in equipment split by country, branch, application and region, respectively. About 10 % of AM equipment is bought by research organizations.

According to the Wohlers report, sales within Additive Manufacturing of metal parts are increasing. **Figure 7** from the Wohlers report [23] shows the number of machines sold for printing metal parts. These figures have to be examined since it isn't clear how many machines were for PBF technologies, or for sand printing technologies from the companies ExOne and Voxeljet. A sand printer is almost solely used within the foundry industry and is thus considered to be for the indirect manufacturing of metal parts. When interviewing the two suppliers it can be estimated that the number of sold machines will increase just as dramatically as it has for PBF metal printers.

AM equipment is just one part of the strategic investments in AM research. Additionally, investments in different manufacturing equipment (powder manufacturing, 3D-scanners etc.) are also being made, as well as investments in building up AM competence.

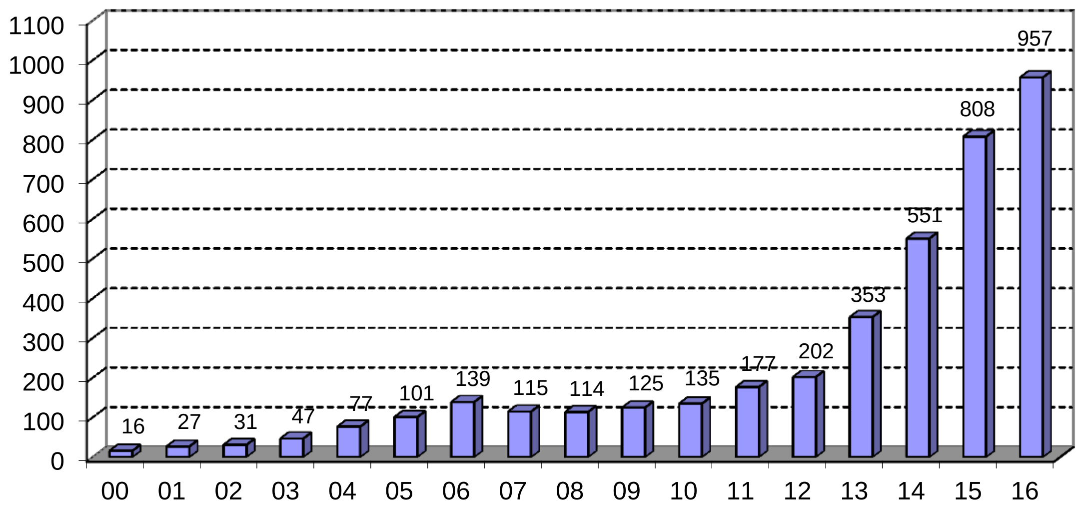

Figure 7 *Number of AM systems for metal parts sold, according to Wohlers report 2017 [23].*

4.3.1. Sweden

For more than 25 years there have been service providers of 3D printed parts in polymers, including companies such as GTP, Acron and Prototal. The latter is a spin-off from a very early investment by Electrolux in 1988, the first 3D-printer purchased in Europe. Electrolux built up an experimental shop in Jönköping at Husqvarna to develop new parts. This was later closed and became Prototal. Electrolux Rapid Development was one of the first to develop LB-PBF for metals in the late 80s in Finland. They started collaboration with EOS and, even today, EOS material and powder development for metals is still located in Turku in Finland.

Xylem Wastewater, former ITT Flygt, manufactures drainable pumps. They installed their first 3D-printer for VAT-polymerization as early as 1986/87 and purchased one of the first machines from EOSsint for laser sintering of sand to make cores and molds. They have now ordered a 3D-printer from ExOne, an S-Max, to continue to develop their supply of spare parts, thus eliminating the need to store tools in their warehouse.

Mittuniversitetet in Östersund was very early in building up a strategic center for additive manufacturing in 2008 and is today involved in making prosthetics and implants for e.g. Karolinska university Hospital. They installed the first Arcam machine in Sweden.

In Örebro/Karlskoga the Alfred Nobel Science Park has formed TTC (Tillverkningstekniskt centrum) which is a collaboration between academy, industry and the Nobel Science Park. Among the partners in this center are Siemens, Saab, Atlas Copco, Lasertech LSH, Exova, Örebro and Karlstad University.

In February 2014 a discussion at a conference in Berlin gave rise to the idea of a Swedish Arena around the AM of metals. The inauguration was the held on 25 of August 2016 with the name Swedish Arena for Additive Manufacturing of Metals and was initiated by Chalmers, Högskolan Väst and Swerea. Industrial partners include Brogren Industries, Quintus Technologies, Carpenter Powder Products, Alfa Laval, Uddeholm, 3D MetPrint, Lasertech LSH, Saab, Höganäs, Siemens Industrial Turbomachinery, Scania, AIM Sweden, Trumpf maskin, Atlas Copco and Freemelt. Örebro University and Karlstad University joined as research partner and more companies and universities are expected to join during 2017.

Many Swedish companies are currently doing strategic investments into research for metal AM. Sandvik Machining Solutions has an AM-center, launched in 2016, with a number of machines for metals from different technologies.

This year, Chalmers had a competence center for AM of metals (CAM2) approved by Vinnova involving 22 companies and 5 research organizations and funding of 36 million SEK (5+5 years).

4.3.2. EU

4.3.2.1. United Kingdom

Universities in UK started very early in positioning themselves in the AM landscape. The welding Institute (TWI), the University of Nottingham, Loughborough University, Cranfield University and Glasgow University were early starters and formed research centers in different areas. Today at least

25 universities and 8 institutes are doing research projects in the field of AM, some of them are listed in

***Table 2** Examples of research areas and equipment for metal AM at selected universities and institutes in Europe*.

British AM initiatives have just recently announced an investment in a 3D-AM center in West Ham, East London. With this announcement, the United Kingdom continues to encourage the use of AM. Earlier this year The British Government's innovation agency, Innovate UK, have granted Additive Manufacturing Technologies Ltd. (AMT) a £624000 grant to refine a new automated post-processing method for 3D printed parts. The Sheffield company will work within a consortium along with fellow British company Xaar.

Innovate UK offer £3 million to UK 3D designers to encourage the implementation of AM in the early stages of design. Read more on: https://www.gov.uk/government/publications/funding-competition-design-foundations-2017-round-1/competition-guidance-design-foundations-2017-round-1

As a part of the strategic research landscape the British Government through Innovate UK is advancing the adoption of Industry 4.0 with roughly €600 million in funding

4.3.2.2. Germany

Germany was also an early adopter of AM technology and started research activities very early on. In **Appendix 5** a map of selected AM players in Germany is shown. In 2008 they established strategic partner organizations to promote research in AM. First out was DMRC in Paderborn with 18 partners. These partners include: Baker Hughes, John Deere, LEGO, Siemens, SLM Solutions, Stratasys, H&H, Liebherr, Parker, Phoenix Contact, Stuekerjuergen, blue production, Eisenhuth, Krause Dimatec, and Rembe.

The internationally renowned Fraunhofer Society Institutes are at the forefront of research activities in Germany and closely cooperate with industry players along the value chain. The Fraunhofer Additive Manufacturing Alliance encompasses thirteen institutes which are based throughout Germany to form the entire additive manufacturing process chain, comprising the development, application and implementation of additive manufacturing methods and processes.

The Technical University of Munich (TUM) and the Swiss technology firm Oerlikon have signed a partnership agreement. Both partners intend to work for progress in research in the field of additive manufacturing technologies. Plans foresee the establishment of a joint institute where research will focus on metal processing.

ACAM Aachen center for additive manufacturing is a member program at the RWTH Aachen campus in Aachen involving university, institute and companies (http://www.acam-aachen.de/). The concept is similar to the Swedish AM-Arena.

4.3.2.3. Other EU countries

Another example is Oslo based Norsk Titanium who differs from other manufacturers of metal 3D printers. They do not sell machines but set up joint ventures where they own the machines and continue to operate them within the joint venture. They were founded in 2007 and in 2016 they were certified as supplier of aerospace parts. Norsk's full rate production RPD™ machines (Gen 4) can produce 22 metric tons of aerospace-grade titanium parts per year.

4.3.3. USA

There is rapid growth in American industry for strategic investments. The $1 billion promised by USA government 2012 to set up centers for advanced manufacturing is intended to create fifteen institutes of which NAMII, also called America Makes, is the most renowned. The center is based under the program National Network for Manufacturing Innovation, and was the first of 45 potential centers. It is based in Youngstown, Ohio, and has collaboration with the nearby university. The center today has almost 200 members in the areas of government, academy, large enterprises, small enterprises and business development enterprises. Within the America Makes organization, almost 50 projects is ongoing involving many of the member partners.

GE has invested in a manufacturing facility that will drive innovation and the implementation of additive manufacturing across the company. The Center for Additive Technology Advancement (CATA) – located near Pittsburgh – will be the flagship center for additive manufacturing, focused on developing and implementing industrial applications. This is GE's first multi-modal site in the U.S., designed as an innovation hub offering training and development in both design and applications. Total investment will be $39 million until 2018.

One organization that has been doing strategic research for many years is DARPA - Defence Advanced Research Projects Agency. DARPA's Open Manufacturing program has three strands. The first is not directly related to 3D printing but looks at bonded composites; 3D printing is the focus of the two remaining strands, the Rapid Low Cost Additive Manufacturing (RLCAM) effort and the Titanium Fabrication (tiFAB) effort.

4.3.4. Asia

In February 2015 GE opened a factory at the outskirts of Pune that fits into the plans for the "Make in India" campaign. Spread over 67 acres (271000 m^2), the plant is among the first flexible factories, where different products for multiple businesses will be built using shared infrastructure, equipment, and people under the same roof. GE is investing about $200 million in the facility.

China is among the earliest countries that started additive manufacturing (AM) research. Around 1990, several groups in China had started AM various AM research efforts, which include Tsinghua university, Huazhong University of Science and Technology and Xi'an Jiao Tong University. After over 20 years, AM research in China has greatly expanded into a wide range of areas from aerospace, defence, automobile, biomedicine to appliance, tooling, micro/nano-fabrication and art design. Currently there exist over 10 large research groups and companies in China involved in AM research listed in **Appendix 4**.

Singapore announced in 2013, according to Wohlers, that they would invest $400 million in additive manufacturing and strive to be among the best in the world. Nanyang technological University has created the “Singapore Centre for 3D Printing”. This includes several of Singapore’s leading technology universities, namely NTU Singapore Centre for 3D Printing, NUS 3D Printing Centers at the Schools of Medicine and Engineering, as well as SUTD’s Digital Manufacturing and Design Centre.

In 2015 The National Additive Manufacturing Innovation Cluster (NAMIC) became part of the Innovation Cluster Program (ICP) led by NTUitive, supported by the National Research Foundation and in partnership with the SPRING Singapore and the Economic Development Board of Singapore.

In 2014, the Technology Research Association for Future Additive Manufacturing (TRAFAM) was launched in Japan. This center consists of 29 members from the academia and industry. The goal of the center is to focus on the development of metal AM machines in regards to their building speed, precision, and build size. In Singapore, the National Additive Manufacturing Innovation Center is running with up to 350 members in the consortia.

4.3.5. Other

Other parts of the world are investing in AM research for metals, and roadmaps have been created in e.g. Australia and South Africa. Brazil is also increasing their research activity. The accumulated number of AM equipment for metal in these countries is only 4.6 % of the total number in the world, **Appendix 3**.

4.4. Ongoing & finished research projects

The amount of funds approved for research projects in various countries is difficult to appreciate, and it can be hard to find information about the projects. However, an attempt has been made to collect available information to try to and make a comparison.

4.4.1. European funding

The earliest AM projects were started in the Frame programme 1 (FP 1 from 1984 to 1987) with the funding of three projects. In FP 7 (2007 to 2013) more than 60 successful projects, spending more than €225 M, of which €160 M was funded by the EU. The Horizon 2020 Framework Programme is at its mid-term. In these 3 years, the funds allocated to Additive Manufacturing and 3D-Printing has reached more than €115 million, which is already 70% of the 7 years of total FP7 contribution to AM.

Some organizations have been more active than others as can be seen in **Figure 8**. Since 2007 the EU has granted €320 million in funding, giving it a total of more than €500 million for the 101 projects that are running and are finished. In all these projects, there are 602 different organizations, universities, institutes and industries participating. AMAZE and MERLIN are two examples of projects related to AM and metals with Swedish participants.

Source: EUPRO database, CORDIS database, own calculation

Figure 8 *Organizations with most involvement in EU FP1 to FP8*

4.4.2. UK funding

In the report; "Mapping UK Research and Innovation in Additive manufacturing" [59], a review of the UK's publicly funded R&D activities in additive manufacturing between 2012 and 2015 has been carried out. **Figure 9** shows the funds given.

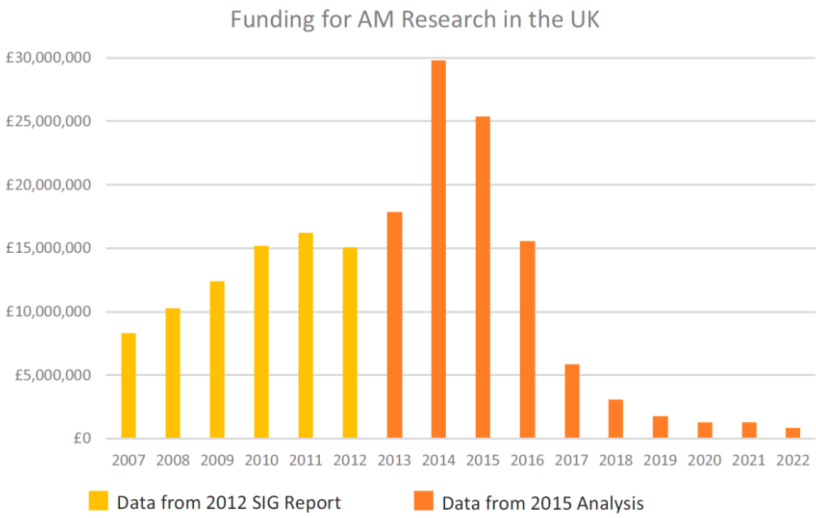

Figure 9 *Spent and granted funding in UK since 2007 according to Innovative UK*

The report shows that research has been attributed to 244 projects, a total of 243 organizations and 165 commercial organizations. The number of academic institutions engaging in research included 41 universities in 2015.

In summary, between 2012 and 2015, there has been a:

- 100% increase in annual additive manufacturing R&D expenditure
- 80% increase in the number of active R&D projects
- 200% increase in the number of industrial organizations engaged in additive manufacturing research
- 71% growth in the science base engaged in additive manufacturing research

When one summarizes the funding it comes to £ 180 million, which is equal to about €215 million between 2007 and 2022. Between 2012 and 2017 the amount of funding is £110 million.

4.4.3. German funding

The Deutsche Forschungsgemeinschaft (DFG) has an annual expenditure of around $50 million for basic research in advanced manufacturing. The following list shows projects for additive manufacturing in Germany:
http://gepris.dfg.de/gepris/OCTOPUS?keywords_criterion=additive+manufacturing&findButton=Finden&task=doSearchSimple&context=projekt

Typically the DFG funds a project with €0,18 million over a two year period. Most of the projects within additive manufacturing are of 2 + 2 or 3 + 2 year periods. Looking through the almost 50 running projects from 2011 to 2017 brings the funding up to a level of more than €200 million.

4.4.4. USA funding

In June 2011, U.S. President Barack Obama launched the Advanced Manufacturing Partnership (AMP) on the recommendation of the President's Council of Advisors on Science and Technology (PCAST). AMP was charged with identifying collaborative opportunities between industry, academia and government that would catalyze development and investment in emerging technologies, policies and partnerships with the potential to transform and reinvigorate advanced manufacturing in the United States. Its first set of recommendations, "Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing," was issued in July 2012 investing $500 million to jumpstart this effort. Furthermore Obama promised funding of $2 billion to start up research at least 15 centers around USA. Find out more at: https://www.manufacturing.gov/nnmi-institutes/

With funding from the Pentagon in 2014, a $70 million digital manufacturing consortium has connected 60 academic institutions, government entities and other organizations to spur manufacturing innovation. The Digital Lab for Manufacturing, Chicago, will serve as a hub for the consortium and is managed by the University of Illinois (UI). Participating industry partners include John Deere, Caterpillar, Rockwell Collins and Procter & Gamble. The industry has spent $250 million in this effort.

Between 2012 and 2020 it is believed that Manufacturing USA – the National Network for Manufacturing Innovation (NNMI) will spend more than $4 billion from national funding in advanced manufacturing of which at least 50% is directed towards additive manufacturing. All the institutes involved in additive manufacturing will get $20 million every year during this period to finance research.

4.4.5. Chinese funding

The Chinese Government Invested 200 million RMB in "Setting up 3D Printing". The Research Institute of China was launched on August 8th 2013 at Zijin Hightech Zone of the Nanjing city, Jiangsu Province. The Institute will combine forces of some best Chinese 3D printing research teams in China. According to the Wohlers Report, China will spend more than $ 5 billion between 2012 and 2017.

4.4.6. Singapore funding

The government will invest S$500 million (US$390 million) over five years to boost country's capabilities in advanced manufacturing, including in the rapidly emerging AM industry. This was announced in the 2013 budget.

4.4.7. National funding in Sweden

Historically, Sweden was doing research and networking to spread information about additive manufacturing. Between 1990 and 1996 the area of AM-projects was financed with 7.6 million SEK. **Figure 10** shows funding in the following years, from 2000 to 2008, from Vinnova [60].

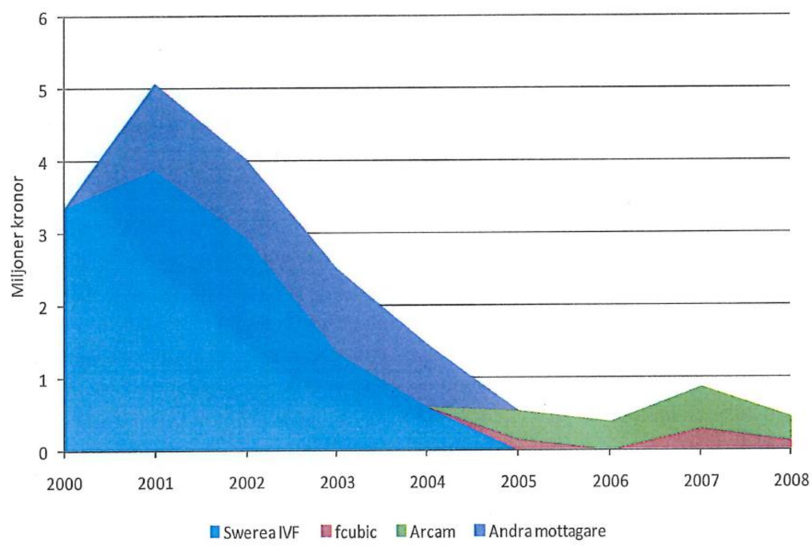

***Figure 10** Spent and granted funding in Sweden 2000 to 2008 [60]*

Since 2011 the number of approved projects within additive manufacturing has increased exponentially. **Appendix 6** shows a list of projects within additive manufacturing and 3D printing collected from a presentation given by Vinnova in November 2016 and web sites of the Strategic Innovation Programmes. Additionally, some projects from KK-stiftelsen, the Swedish Foundation for Strategic Research and regional funding were added. Only projects with relevance to metals are listed. **Figure 11** shows an estimate the sum of approved funds between 2011 and 2020. The total sum invested in research for metallic materials between 2011 and 2020 is approximately 190 million SEK.

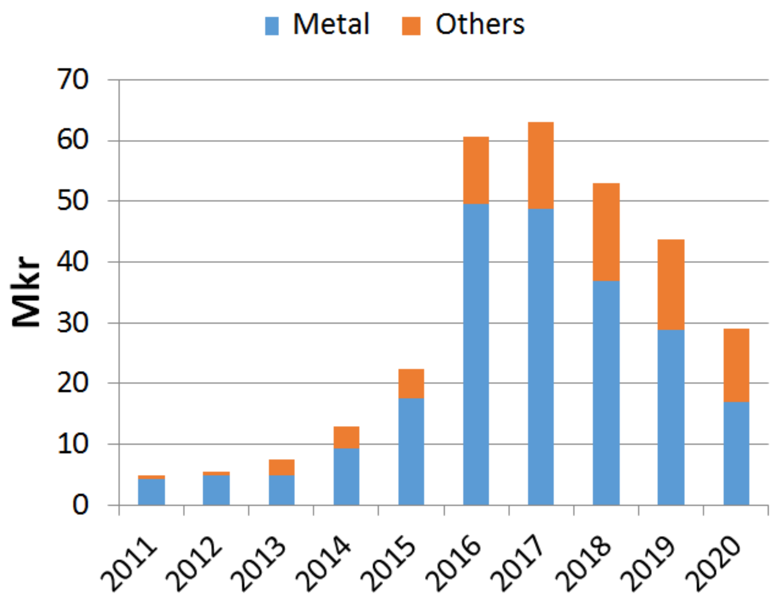

Figure 11 The sum of approved funds between 2011 and 2020 for AM and metal. The information is extracted from Vinnova, KK-stiftelsen and the Swedish Foundation for Strategic Research and some additional information from universities regarding regional funding

4.5. International conferences and seminars

There are too many conferences in the field of additive manufacturing. It is difficult to classify them and indicate whether one is better than another. The overall result of all these events are that it makes great opportunities for networking. Some examples of the conferences include:

- Inside 3D printing http://inside3dprinting.com/
- IDTechEx http://www.idtechex.com/3D-printing-europe/show/en/
- 3D Printing and Technology http://3dprinting.conferenceseries.com/
- Additive Manufacturing + 3D Printing Conference & Expo https://www.asme.org/events/am3d-conference
- ACCELERATING 3D MANUFACTURING http://www.rapid3devent.com/
- RapidPro 2017 http://www.rapidpro.nl/home-en-US
- Fraunhofer Direct Digital Manufacturing Conference http://www.ddmc-fraunhofer.de/
- Materials Science and Technology http://www.matscitech.org/

Fairs and trade shows:
http://www.amshow-europe.com/welcome-additive-manufacturing-europe
http://www.amshow-americas.com/welcome-additive-manufacturing-americas
http://www.asiamold-china.com/guangzhou/en/visitors/events/concurrent_event.html/
https://www.mesago.de/en/formnext/home.htm

Web sites where many more events and conferences can be found include:
http://www.metal-am.com/metal_additive_manufacturing_industry_events/
https://www.americamakes.us/news-events/events

4.6. Market situation for important companies in the AM-industry

Gartner evaluates new businesses and emerging technologies and place them on a so called hype curve. It is interesting that, over a period of only 8 years, AM/3D-printing came and disappeared again to finally become a commodity **Appendix 7**. This is also roughly the same way the stock market has reacted to AM. Looking at the two major publicly traded companies in the USA, Stratasys and 3D Systems, they boomed from 2012 to 2014 with 1000% and 600% respectively. From this peak they dropped to roughly 75% by mid-2016.

Having this in mind it is important to look at which companies are growing, and also why they are growing, to understand what type of research they could be asking for from external resources. In **Appendix 8** there is a list of selected companies involved in 3D printing of metal parts, or supplying technique for printing molds for metal casting, and their market caps and share values.

4.7. A new workforce in the AM-industry

Throughout the history of industrialization, innovative business models, process improvements or technological breakthroughs have brought into question job sustainability in certain industries. Globally, jobs transformed and workers adapted with new advances in automation and technology.

GE has published "The Future Workforce: Advanced manufacturing's Impact on the Economy" a white paper describing some of the needs and also the positive impact advanced manufacturing has in shaping the future of work.

In this white paper the advanced industry includes far more than just additive manufacturing, in fact it accounts for 13 percent of all jobs in the U.S. and contributes $3.1 trillion to the economy. In addition, for every advanced manufacturing job created, 3.5 jobs are supported through the supply chain, and the average salary for a technologist in the industry is $95,000.

In the opposite corner is the announcement from Makerbot (3D-printers for plastics) that they laid off 30% of their workforce, which means a staff reduction of roughly 150 employees. The reduction of staff began in April 2015 and, so far, almost 55% of the workforce has been made redundant.

5. State-of-the-art

5.1. Technical state-of-the-art

5.1.1. <u>Design</u>

Due to the nature of the layer-upon-layer addition of material in the AM process, completely new types of design features and functions have become possible. With AM, geometries and other design features in materials that were previously impossible to produce with conventional manufacturing are now possible.

Design for AM incorporates both the visual design of the components, but also other features, such as its mechanical properties. By utilizing AM, value can be added to components when design is considered, both from a geometrical and physical perspective. Value can be added to components through:

- more complex shapes
- include moving parts in an assembly printed as a single component
- part consolidation - where several parts are replaced with one single part
- customized parts tailored specifically to the individual purpose
- light-weighting through topology optimization and lattice structures

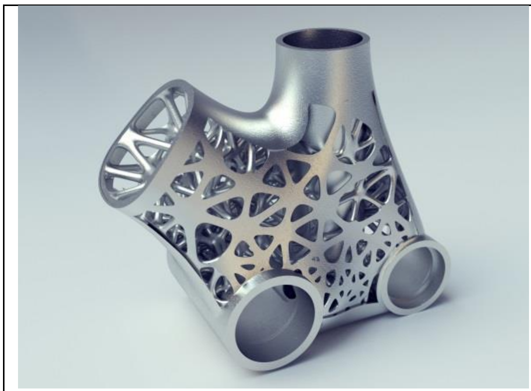

Figure 12. *Light weight structure, part of a bike assembly designed by Fraunhofer Institute. Manufactured in titanium by EBM. Curtesy: AIM Sweden AB.*

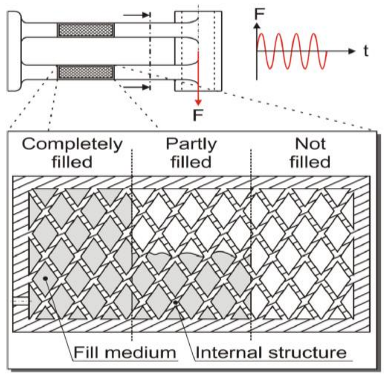

Figure 13 *shows an example of a complex shape where internal structures have been used to improve a components damping performance. The structure is covered by a patent filed by Siemens AG, (DE 10 2010 063 725 A1). From DMRC*

Although these design features seem promising, the layer-upon-layer methodology also creates certain limitations that must be considered when designing a part. It is clear that one critical issue is how to design an optimal AM part, particularly for metal AM. Metal AM industry has, so far, been inspired too much by polymer AM in terms of design. This has created issues as, for example, support structures are easy to remove in polymeric parts, but are difficult and sometimes impossible to remove for metal parts, so designing a part to avoid support material, for example, should play a much greater role in metal AM. Most AM technologies differ in how the resulting material behaves, and on whether or not they require support material, or whether or not the produced part has anisotropic properties. For this reason, each AM technology may require some individual design guidelines.

There has been a lot of effort by researchers at DMRC, Lazer Centrum Nord and Duisburg University to set up design rules that can be used in various manufacturing techniques. **Figure 14** is an example of what is needed and how different rules can be clustered together. This is information received from correspondence with DRMC.

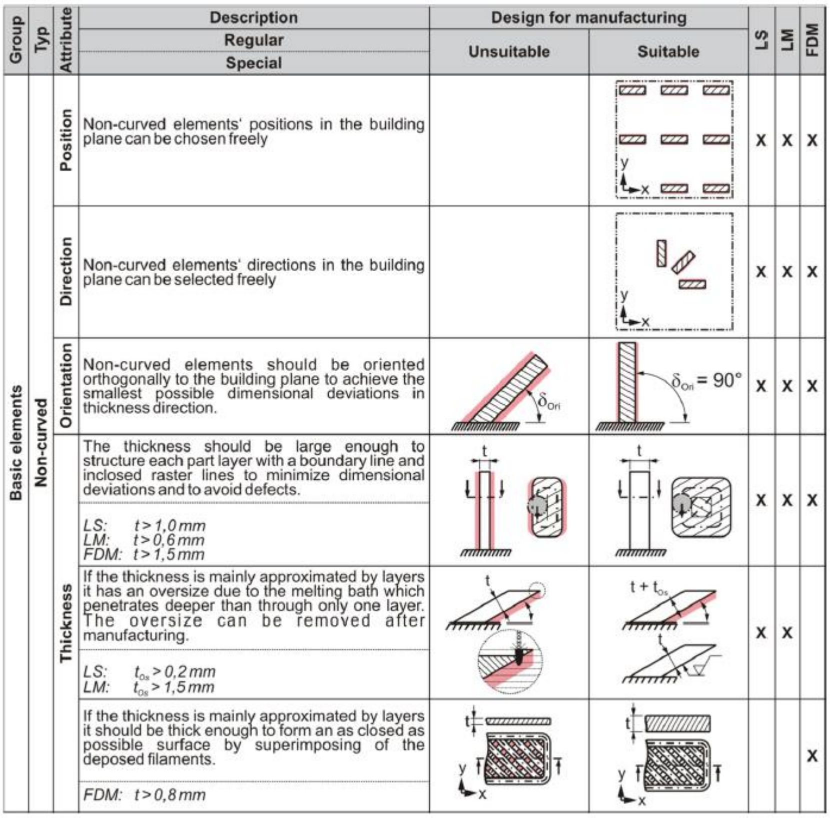

Figure 14 *Example of design rules for additive Manufacturing. From DMRC.*

Based upon this, there are some constraints that need to be taken into considerations that cannot be controlled in specific guidelines. For the PBF processes in metal, the material is usually considered to be fairly isotropic, and that consideration can be excluded. However, the following are examples of general guidelines for designing geometry for AM today:

- ***Part orientation*** - this influences the possibility to build certain geometries due to limitations i.e. gravitational forces or need for support structures in metal components. By using the most efficient part orientation, the need for support can be kept to a minimum.
- ***Part size*** – all AM machines have a limitation when it comes to size, whether it be the build chamber size or the range of a robotic head.
- ***Support structures*** – For metal AM, and especially PBF, support structures are necessary to either help and/or overcome gravitational forces, but mostly to remove heat generated stress concentrations, and to anchor the part to the build substrate to prevent warping. One technique that can be used is to integrate the support structures as a feature of the final component. This, in turn, gives new rules to follow when, for example, topology optimization is used to optimize the design of a component.
- ***Post processing*** – Depending on what surface finish is required; post processing must be considered when designing an AM part. AM is, today, a process that does not deliver mirror flat surfaces. Instead, the surface roughness should be comparable to a sand cast part, see **Figure 15**. During design, it must be taken into account that, if post-processing is needed, material may need to be removed to achieve a specific surface finish, or material properties might vary if the part is HIPed or heat-treated.

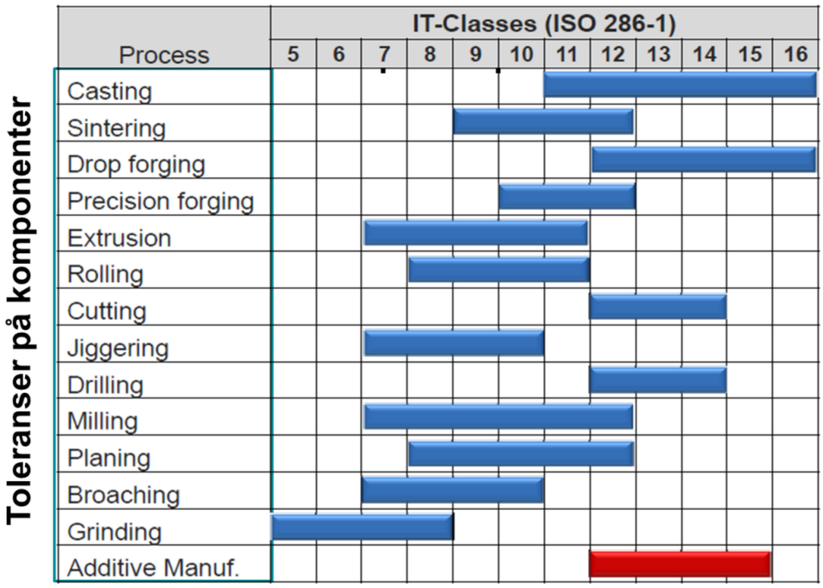

Figure 15 *Comparing surface roughness after various processes. From DMRC.*

One major issue to address is the variety of modelling software available on the market. Most CAD-programs do not print directly from their native formats, but rather communicate to the AM systems via neutral formats such as *.stl and *.stp. The risk, when converting from one format to another, is always a loss of information if various software do not communicate in the same way. Therefore, communication between software is particularly important when an optimization has to be done with, for example, the use of topology optimisation software. The following example is from a presentation made by Bombardier in 2015. The topology software does not export to a native CAD-format; you have to “translate” it in order to continue developing the part.

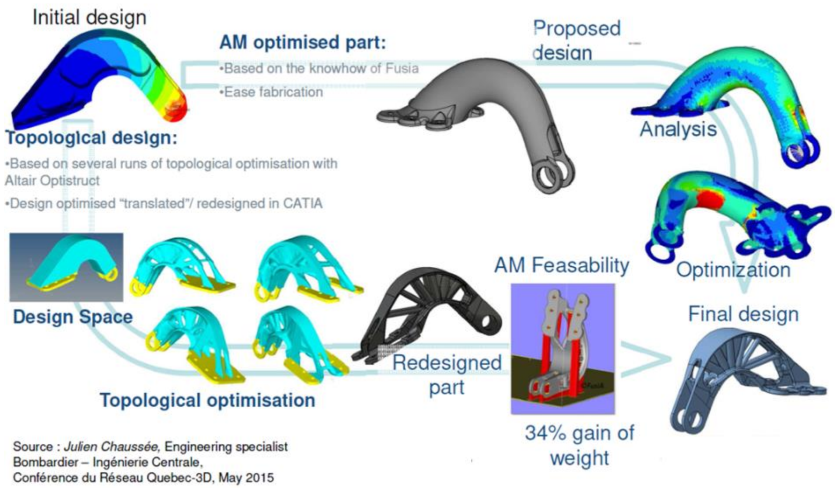

Figure 16 *Example of design to optimize a bracket for weight. From Bombardier*

AM parts are often compared to castings, as a reasonable facsimile, since melting of powder with a laser, plasma or an electronic beam is comparable to what happens in a casting on a micro scale. There are the same micro porosity problems; they have to be fed with liquid metal to avoid porosities. When liquid metal turns to solid it shrinks and dimensions needs to be adjusted. The shrink is not equal in all 3 dimensions since parts are not allowed to shrink freely in space but are obstructed by geometry (in a Foundrymans world this is pattern makers allowance). So rules have to be made for each part to compensate for shrinkage. Today, the PBF processes use scale factors which are used to scale the part to compensate for this shrinkage in each dimension. These scale factors are, today, based on trial and error iterative testing, so simulation is needed.

Understanding the process of 3 dimensional melting can also be beneficial when designing an AM component. As melting and cooling takes place rapidly, and the melt pool is considerably small, it is possible to incorporate different melting strategies to vary the microstructure on a microstructural level. In Figure 17 a picture is shown where the colors represent the orientation of the individual microstructural grains in a 2 cm long component. By using various melting parameters, the texture can be varied in different areas of the component. This feature can potentially be used to produce material with specifically tailored microstructures at various locations in a component.

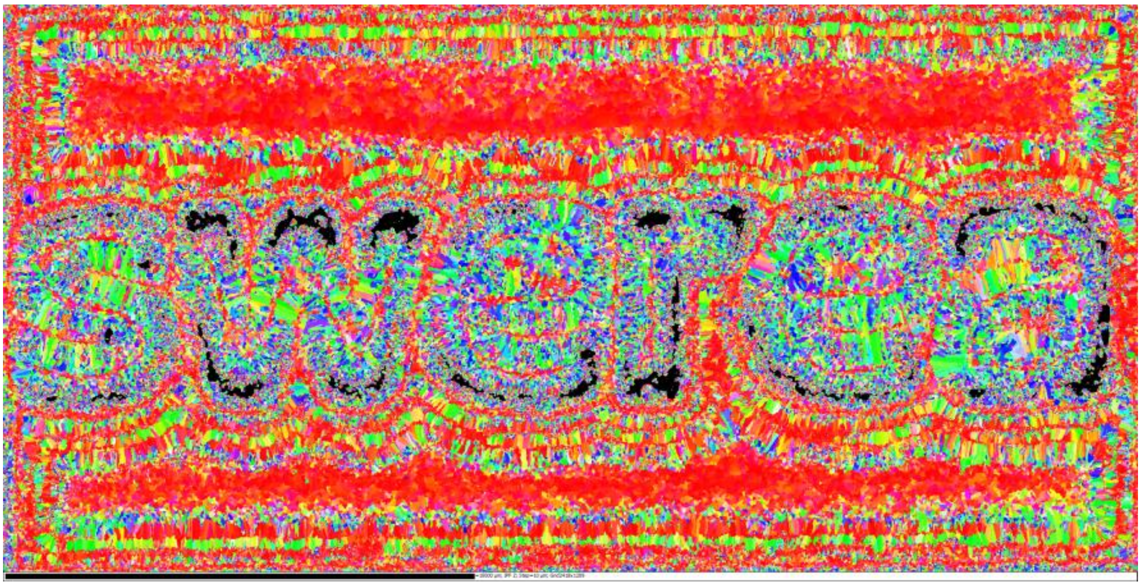

Figure 17*. An Inverse Pole Figure from an Electron Beam Backscatter Diffraction measurement. The colors represent the grain orientation. In this image, a polished sample 1,2 x 2,4 cm made in Inconel 718 is presented. Curtesy: Swerea KIMAB AB*

When designing a completely new part, adoption of numerical simulation at an early stage leads to optimized designs and reduces the number of physical prototypes, all of which point toward a shorter time to market. A high-fidelity simulation can reflect reality closely and serve as an accurate predictor of a design's performance by including all of the physical phenomena involved and being able to describe the interactions as they happen in the real world. The level of accuracy delivered by a Multiphysics analysis has become the norm for an increasing number of users in industry.

The majority of the users of metal printers agree that standards will ease the way for metal parts manufacturing where design guidelines and design standards set the way of achieving well defined components with certified material properties.

5.1.2. Modelling and simulation

Research in the field of AM is performed all over the world at a multitude of locations. Basically all centers use simulations to build understanding and to improve the process. In some cases the work has led to commercial or open software packages which can be used in production planning. An overview of those can be seen in chapter 3.2.4.

There are a variety of topics where simulations aid research. Apart from production planning, related simulations are used:

- to capture the shape distortion in the building of a component so geometric adjustments can be done in advance
- to find the residual stress state in the ready component which can be disastrous to its load carrying capacity
- to improve the building sequence and/or energy deposition in order to improve the state of the component.

More basic research related topics include:

- Melt pool dynamics, which has its origins in weld simulations where a lot of research has been done for different techniques.
- Machine dynamics is very much related to the quality of the melt pool and, specifically, for powder bed machines is directly related to the quality of the layer.
- Material compositions targeting AM processes is a very important today, since there is a lack of materials optimized for the process
- Powder interaction is related to the sintering of components made with such a technology

The list is not complete. It is compiled for the reason to given an overview of the wide range of topics that exists where simulations are used as a help to achieve greater understanding and more rapid development.

Since simulations are widespread and used by almost everyone in the field, it is hard to point at specific research teams. There are even conferences which are dedicated to simulation of the AM process. (i.e.: the 1st ECCOMAS Thematic Conference on Simulation for Additive Manufacturing). However, a small list of research groups that have been in the business long enough to generate software includes:

- Lawrence Livermore National Laboratory they take a multiscale approach of both the powder and the complete part using their in house code ALE3D.
- The Institute of Photonic Technologies (LPT) at Friedrich-Alexander-Universität Erlangen-Nürnberg teamed up with GeonX to supply laser melt pool simulation for GeonX Virfac.
- From the ISEMP group at the University of Bremen at a spinoff called Additive Works has launched a code - Amphyon that also predicts and compensates for the distortions caused by the thermo-mechanical AM process.

5.1.3. <u>Materials</u>

The use of powder as a raw material constitutes an important strategy in metal AM. At the same time, Sweden has a strong position in metal powder production and a strong knowledge base for powder technology. The key challenge today for AM of high-quality components is the limited choice of materials with developed process parameter recipes, see **Table 4**. The materials with developed recipes can only be acquired from the equipment suppliers together with the respective process recipes that assure the fabrication of near-full density AM components. At the same time, powder manufacturers indicate the presence of a large number of materials; see **Appendix 10**, where the mechanical properties (powder size, particle size distribution, flow, etc.) would also satisfy the requirements of the hardware for powder-bed AM technologies. However, there are no stablished process parameters for these materials. At the same time, it is important to note that a number of advanced users have developed in-house process parameters for the alloys of their interest that are not commercially available (e.g. Michelin, GE, Airbus, etc.).

As stated above, only a limited number of alloys are available today for powder bed fusion and do not satisfy the needs of many end-users. At this stage, more or less all powder for AM is provided via the equipment manufacturers, with a high cost of the powder (between 150 to 800 EUR/kg depending on alloy and supplier). A current trend in a growing market for metal AM powders is that the large AM powder users are looking for other supplier than the machine vendors to supply powder, e.g. the large powder producers. The reason is that current supply of AM powder via small-batch fabrication by Vacuum Induction Gas Atomization (VIGA) or Electrode Induction melting Gas Atomization (EIGA) cannot satisfy the demand on powder volumes, e.g. feeding even one large quadrupole-laser machine requires mixing of several powder batches and, hence, such a solution is not sustainable. In the case of stainless steels and iron-based alloys, conventional gas atomization with nitrogen is feasible. The increasing demand in powder for AM means that large scale manufacturing capability is crucial to supply the demand, and can also be an advantage when volumes are increasing. Sweden is, by far, the largest producer of metal powder in the world (about 25% of the global market), but only a small fraction of its powder is used for AM applications. Hence, the creation of a research and technological platform for materials development for AM is of vital importance for Swedish PM industry as well as international AM community that requires a transformation of the powder supply for AM industry from niche to standard products, with clearly defined requirements.

Table 4 *Qualified materials and powder for PBF-LB and PBF-EB (according to equipment providers)*

Technology	Alloys	Powder
PBF-LB	12 (Al-Si, Co-Cr, IN718, IN625, Hast.X, Fe18Ni9Co, 17-4PH, 316L, PH1 steel, GP1 stainless steel, CX steel, Ti-6Al-4V)	20
PBF-EB	II. 4* (Ti-6Al-4, Ti, Co-Cr, IN718)	4

** Additionally, γ-TiAl a standard proprietary material for Avio Aero*

Apart from the above materials, successful trials have, according to Arcam, been made with several materials with PBF-EB. Examples are different nickel based superalloys, stainless steel, tool steel, Invar, aluminium, cemented carbides, copper, beryllium and niobium.

5.1.4. Productivity

Additive manufacturing is frequently considered as a production process for comparison with established subtractive processes such as metal cutting processes (milling, turning, drilling etc.). However, the potential and scope of AM is far beyond just a production process and, from a lifecycle perspective, it is a manufacturing paradigm shift in its own right. Although in its infancy, it has clearly demonstrated that AM is influencing the way products can be designed, manufactured and marketed. Upstream and downstream supply chains, including the shop floor processing chains, are unique to the AM paradigm and have a strong potential to reshape the manufacturing systems of the future.

Productivity in AM has been a topic of hot debate since its rise as a competitive alternative to subtractive processes. Despite unlimited freedom in design, mass-customization in production along with diversity and flexibility in control of engineering properties of the builds, AM has been criticized as a slower and expensive process in comparison to well-established mass production subtractive technologies. Productivity in AM can be looked at from several different perspectives but at least the following four are of vital interest:

- Stand-alone process
    - The productivity parameters, which in this case include automation in material handling, flexibility in process parameters, build rate, in-situ process monitoring preheating and cooling durations and automation in post processing at the machine level.
- Process chain
    - Sequence of processes requiring AM to fit in the conventional production environment where redesigning for AM is not of interest but post-processing such as heat treatments, machining etc. are essential to get the final product. Productivity of such a process chain can be strongly influenced or even driven by the productivity at the AM machine level
- Production lifecycle
    - Redesigning for AM to consolidate multicomponent parts/products with an aim to reduce external or internal supply chains providing the components necessary in conventional design of the parts/products. In such a case where products are still designed for conventional production, the consolidation potential of AM is exploited to reduce the number of components, thus supply chains, and lead times significantly. Productivity in such case will be determined very much by the intensity of consolidation achievable in a given set-up
- Manufacturing system
    - This includes designing the products for AM, supply of the raw materials for AM, AM driven process and supply chains including business models characterized by parameters such as manufacture on demand, local or mobile manufacturing, blueprint manufacturing. In this case, productivity enhancement can be determined through reduced supply chains, shorter lead times, reduced logistics and warehouse management, access to new markets etc.

<u>Productivity at the machine level:</u>

- In the case of powder bed fusion (PBF) machines, automation for powder handling, charging, part removal, powder cleaning and recycling is being considered in the design of emerging industrial solutions.
- In the case of laser based machines the build rate is being increased with increased power and number of laser sources

- To doing it right the first time, in-situ process monitoring is also installed in emerging industrial machines
- New machines for PBF-Laser Beam and PBF-Electron Beam have one or more of these productivity features
- Another interesting productivity feature is the combination of additive and subtractive processes where the post machining can be completely avoided and the parts with high quality surface finish even on complex internal features is also possible. Matsura LUMEX Avance-25 and DG Mori Lasertech 65 are examples of such solutions in the PBF and DED (direct energy deposition) technologies

Productivity at process chain level

Modular industrial solutions with the flexibility of expanding capacity, adding pre and post processing steps in the process chain is the productivity enhancement approach developed by Additive Industries in their industrial solution named MetalFab1 (https://www.youtube.com/watch?v=-mxGwJ9ftTE)

5.1.5. Process stability

Process stability is essential for AM of metals to be a validated manufacturing process. Scattering in the process can be tolerated, as long as the final properties of the component can be predicted to be within a certain range. The properties will be the result of design, material and process and the three factors are closely coupled to each other. The construction must always be made based on the lower limit of the properties. Today, process variations occur both between different machines from the same model and build position in the build chamber. Process stability will be influenced by both hardware and software and new solutions and different control systems are continuously being developed to improve stability.

The possibility of making unique parts is one of the great advantages with AM, but requires new approaches regarding predicting of process stability. Gradually, experience will be gained to make better predictions. However, to speed this up, strategies are needed for optimized test matrices and valid parallel conclusions that can be drawn.

However, scientific studies have been published to investigate an understanding regarding process stability, and the various machine suppliers are working on systems to tackle these issues. Some examples of today's state-of-the-art ways to maintain a robust process are listed below:

- **Process monitoring in-situ** – using camera based systems to monitor the melt pool, both for PBF and DED processes. For PBF's the camera based systems are also used to analyze the powder coverage.
- **Well tested process themes** – the vendor guaranties process stability for selected materials and geometries
- **Experimental studies –** studies conducted both from vendors and research parties to identify product quality through iterative processes with destructive and non-destructive testing
- **Open source test platforms –** both NIST and EWI are developing open source laser systems to test and verify various monitoring systems (Wohlers 2016 [23]).

5.1.6. Heat treatment and HIP [61]

After AM, the material needs to be heat treated in order to get the desired microstructure and properties e.g. hardening of tool steels. One exception is TiAl6V4 manufactured by PBF-EB that, by chance, gets the wanted microstructure as-manufactured, eliminating the need for heat treatment.

For PBF-LB, annealing of the component after manufacturing is needed in order to relieve the stresses and avoid distortion.

For binder jetting, sintering of the as-built component takes place in a furnace to evaporate the binder and close the porosity.

Additionally, for some applications, further reduction of porosity by HIPing can be required. Some benefits from HIPing AM parts can be:

- ~100% theoretical density; longer and predictive life time, lighter and/or low weight designs
- Improved material properties; increased mechanical properties, reduced property scatter, stress relief of AM parts
- More efficient production vs. traditional manufacturing; AM combined with HIP can reduce energy use up to 50%, AM combined with HIP can reduce material costs up to 90%

For additively manufactured medical implants and aerospace components, especially for structural and load bearing critical components, HIP is today an industrial standard and, for these applications, it is getting more and more common to include the heat treatment cycle directly in the HIP cycle. Advantages are improved fatigue properties since the stress concentrations from the defects are eliminated, see **Figure 18** and **Figure 19**.

"AM components can be HIPed and heat treated using conventional specifications, but there is an opportunity to optimize the HIP and heat treatment for AM components to minimize distortion during processing", says S. Davies, Bodycote [62]. In the same article P. Henning, Quintus Technologies AB, claims "With the HIP densification and simultaneous heat treatment, the cost of operations goes down, and HIP becomes accessible to other high-performing components".

Quintus Technologies and Oak Ridge National Laboratory are involved in research aiming at optimizing HIP-parameters for optimum properties and understanding of the mechanism of the involved phase transformations.

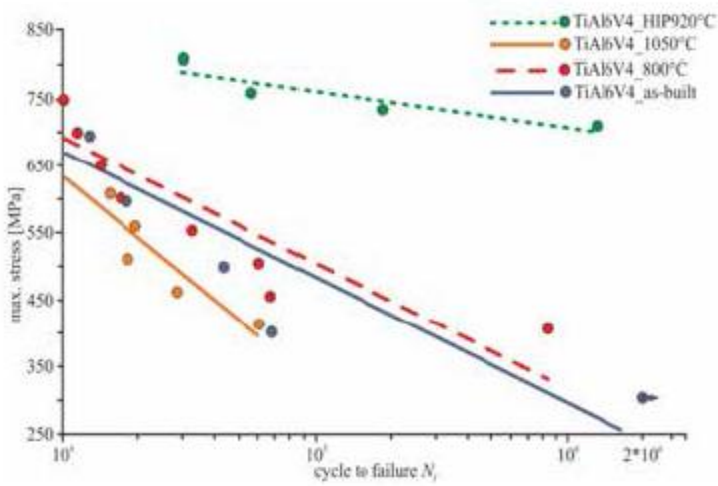

Figure 18 *Fatigue data for PBF-LB Ti-6Al-4V (from "On the mechanical performance of structures manufactured by Selective Laser Melting: Damage initiation and propagation", S. Leuders, University of Paderborn, Germany, as presented at AMPM2014, MPIF, USA)*

POST PROCESSING Ti6Al4V, Gr2 Ti
Heat treatment
Hot Isostatic Pressing (HIP) is recommended for fatigue-loaded components.
The following HIP parameters are recommended:
– 920° C
– 100 MPa
– 120 minutes

Post Processing CoCr ASTM F75
Following support structure and powder removal, it is recommended that the parts undergo hot isostatic pressing (HIP) with the following parameters:
— 1200 °C
— 1000 bar argon
— 240 minutes
— Free cooling rate

Figure 19 *Aram's data sheet – recommended HIP cycle and heat treatment*

5.1.7. Surface preparation

In general the post-process treatments used on conventional produced parts are applicable to AM produced parts. The following lists the need for post processing for surface finish for AM:

- Unconsolidated raw material must be removed from the surfaces and the interior of the parts. Loose metal powder is typically removed using brushes, compressed air and media blasting.
- Printed part and/or build support structures need to be removed by hand or by wire EDM. Sometimes, it is perceived as a time-consuming step.

- Bringing the part surface finish and dimensions to the desired level. The degree of finishing depends in general upon the end use of the part.
- Metal parts made by powder bed fusion techniques may be shot-peened, bead-blasted, or blasted with the same powder used to build the parts. These processes may, in some cases, improve the surface finish and the mechanical properties.
- Metal AM parts are often heat treated to relieve internal stresses prior to removal of the support structures. This step may be followed by post-HIP (Hot Isostatic pressing) to cure micro-cracks and heal any porosity in the part. A third step is precipitation hardening and solution heat treatment to strengthen, harden, or provide homogeneity to the material.
- CNC-based milling and grinding are used to improve the functional properties and appearance of a parts surface. However, the main reason why such post-processes are needed is that the AM build parts fails to meet the dimensional accuracy or surface finish requirements. Vibration grinding and micro-machining processes combining a chemical reaction at the surface with a removal process driven by fluid flow are two examples of surface finishing techniques.
- Final inspection using applicable NDT techniques such as fluorescent penetrant inspection, radiographic inspection or CT-scanning.

5.1.8. Product quality & NDT [63] [64] [65] [66] [67] [68] [69] [70]

Quality assurance of AM parts is a crucial aspect for industrial implementation. The various facets of quality assurance span in-situ monitoring and control methods, AM process stability, repeatability and reproducibility and non-destructive post-AM detection and control of defects. Developing ++Quality qualification and NDT are thus key challenges. A number of techniques have been reported:

- **Feedstock quality**
  - Several techniques exist both for characterizing metal wire and powders. Laser light scattering and imaging are most common
  - Particle size distribution is a key factor but successive sieving is slow and not suitable for in-process monitoring. Particle size distribution measurement using laser light has been investigated and can be implemented at low cost
  - Camera or shadow projection systems with image analysis can be used to automatically estimate particle morphology and particle size distribution of a stream of particles getting very comprehensive statistics
  - Machine vision monitoring of the powder may be the only stand-off process capable for in-situ quality control
  - In-line measurement systems are commercially available for measuring wire diameter and ovality (DED)
  - There is an absence of standardization for powder characteristics which is likely to continue since each system has its own requirements (size distribution and flowability)
  - The existing methods to measure flowablity of powders like pouring it through a funnel (Hall, Gustafsson or Carney), measure angle of repose, powder reometer measurements etc. have limited applicability for AM-powders and the AM applications

- A method to measure spreadability of powder would be useful and attempts has been made on different universities
- Recycling of powder is critical. However, challenges exist (oxidation and absorption of moisture and "heat treatment" of particles)

- **Control of build environment**
  - monitoring includes chamber gas state, thermal characteristics, material delivery (powder bed and wire/powder feed rates), and laser characteristics (power, beam spot size, focus, and position)
  - Temperature monitoring is used of the build platform, powder bed (if process applicable), melt pool and build chamber
  - The dominating techniques are pyrometry, thermocouples, and infrared imaging
- **Control of build characteristics**
  - Vison sensors are frequently employed to catch formation of defects. Cameras and image processing are common (offered commercially from EOSTATE from EOS and 3rd party vendors). The biggest challenge for vision systems is to know how to handle data and which actions to take once defects identified
  - Thermal imaging is also frequently used. A technique which is used in PBF-EB collects a still image of the surface upon the completion of each layer. Near-infrared images are captured and image analysis applied to yield 3D porosity maps of the component
  - High-speed infrared imaging and optical imaging is used in PBF-EB to track the process. The images allow for prediction of the surface temperature during the deposition process and estimation of the temperature gradient and liquid–solid interface velocity
  - Strain gauges have been used, though rarely, to interrogate residual stresses in-situ
  - The height of the build (in a wire-based DED) has been measured using the average height of each layer, determined using a vision system comprised of CCD camera
  - One major challenge is that current AM machines are not equipped for closed-loop feedback systems
  - Data storage and traceability is also a challenge which will become a significant cost for the industry
- **Quality control of produced components**
  - NDE. Relative to process monitoring, there is relatively little research dedicated to non-destructive evaluation of AM parts
    - X-rays and X-ray tomography (CT) are used to detect defects, to interrogate inaccessible features, and to confirm the effectiveness of post-process treatments and to qualify as-manufactured AM parts. A limiting factor is that the detectability varies significantly. Another major limitation is the inability to reliably detect cracks in specific directions. High-resolution, high-speed, and geometrical complexity are also challenges for CT. Health and safety issues is also a concern which will discourage industrial adoption
    - Penetrant Testing has been evaluated for the detection of surface defects but the irregular and rough surfaces present in AM parts makes it difficult to use
    - X-ray diffraction is the most commonly reported method for measuring the residual stresses in AM parts. The method is however surface-sensitive. Neutron diffraction has also been used. Comparing the build before and after

removal from the substrate by using a co-ordinate measurement machine is also used
        - As-built test specimens and parts still exhibit considerable surface roughness, which can be only moderately improved. Contact profilometry is commonly used to characterize surface roughness. Laser or 3D optical profilometry are also employed. Surface roughness and porosity close to the surface of as-built specimens has been shown to have a significant impact on the fatigue performance of AM parts. Blasting and peening has been used to reduce surface roughness and to improve fatigue life
        - Acoustic/ultrasonic investigations of microstructure and mechanical properties are an interesting approach. The techniques might however, require surface polishing to ensure full contact (i.e. semi-nondestructive)
        - Acoustic waves have successively been used to detect defects and to correlate to density. Acoustic waves have also tentatively been used to map grain structure but the small grain sizes in AM compared to conventional parts are a problem. The sensitivity of acoustic techniques to surface roughness is also a problem
        - Structured light can be used to monitor build accuracy both during processing, and to measure finished part dimensional accuracy and tolerances
    - Mechanical Properties and Performance
        - Parts built via any additive manufacturing process are naturally anisotropic. Unfortunately, and despite the many studies that have examined porosity as a function of process parameters, very few have linked the results to mechanical properties. Mapping porosity to thermo-mechanical properties (static, and cyclic) and using the data to determine which NDT methods to use as well as to determine the probability of detection a critical defect size would be valuable
        - Ultrasound has been used to quantify the dynamic elastic modulus of AM samples. Resistivity / conductivity i.e. eddy current, and impedance computed tomography (ICT) have also been employed to infer mechanical properties
        - There is a general lack of data on fracture toughness and fatigue strength. There is also a need to establish relationships between surface characteristics (roughness, porosity/waviness) and toughness and fatigue strength
- **Standards and qualification**
    - There is a need for standardized protocols for post processes such as hot isostatic pressing, heat treatment and shot peening. NDE can here play a role in understanding the effect of these processes on final part properties
    - Standards are also critical to ensure machine-to-machine consistency and calibration to ensure optimal operation and performance
    - Qualification and certification guidelines are, in general, lacking

5.1.9. Automation & digitalization

Additive manufacturing, particularly if a part has not been specifically designed for metal AM, is one of the most man-hour intensive production processes out there today.

The digitalization areas in the field of AM production can be simplified to:

- **Design:** where the AM technology allows for optimized structures. Today optimization is common, but the restrictions imposed by the AM process are more or less in operator knowledge today.

- **Process planning:** where the tools to predict the outcome are practically non-existent. Basically all current process planning tools need a knowledgeable operator. Each machine is a unique individual that gives different results dependent on where in the machine the building takes place. An operator must tweak the building parameters accordingly. The material route in the factory is not standardized for additive manufacturing. The planning of the production as a whole for AM is made manually because of the lack of connection to the Manufacturing Execution System (MES). Usually AM is not part of the production as a whole. There are no software tools that can comply with the hierarchical structure of ISA-95 which is the dominant standard for developing an automated interface between enterprise and control systems. **Figure 20** shows a scheme of the various digital process steps for a component.

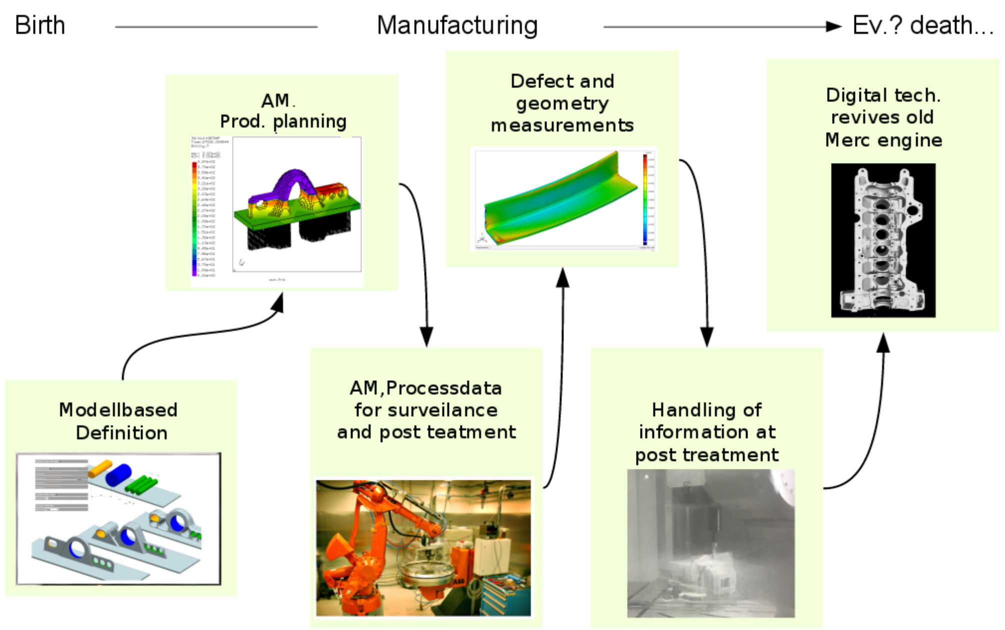

***Figure 20** A schematic showing the digital process flow in AM manufacturing.*

- **The AM process:** where the generated data from monitoring and PLC are accessible but not used for data analysis and feedback.

- **Geometry measurements:** where the geometry of the built components is measured. The measurements generate point clouds, often in very large amounts. There exist some systems for that, but not directly developed for AM

- **Non Destructive Testing**: For load carrying components, it is essential to determine the state of the material. This is often included in certifications which are mandatory in some applications. The data generated from NDT is not generally used for feedback loops

- ↘ **Post processing:** usually the AM components needs post-processing to be used in combination with other structures. The handlings of the component in the post-process are made by hand, and is much more labor intensive than what is common with other components.
- ↘ **Circular economy and similar:** Remanufacturing, Spare parts on file, Continuous improvement, and so on, are techniques that have the potential to play an important role in the future, but play a very minor role in AM development today.
- ↘ **The Holistic point:** Dedicated software tools are used in each step of the product to market chain (simply put: design -> production planning -> control -> market). But there are no standardized protocols for the information transfer between these tools. Operators must manually convert file formats, and the software tools need operators that really know the machines.

Software development for the use in AM is under heavy development. The manufacturers of proprietary software tools are today very active. The AM arena has, until now, had an open approach to software tools and knowledge as a whole.

- ↘ Siemens are working on incorporating the NX-suite into their production control system.
- ↘ Several minor companies have developed tools for the prediction of geometry deviations and residual stresses generated by the AM process.
- ↘ Optimization tools have been on the market for approximately 15 years.
- ↘ There only exists a handful of measurement equipment manufacturers making machines suitable for AM components.
- ↘ The lack of standards in data interfaces and machine interfaces creates a very fragmented digital world.

5.1.10. Production chain [71] [72] [73] [73]

Flexibility in manufacturing operations is becoming increasingly important due to, for example, increasing market demand volatility and shorter product life cycles. AM technologies show great potential in adding flexibility to manufacturing operations through nearly unlimited freedom in product design, product mix flexibility, decentralized production and the ability to produce new product variants in a short period of time. In order to fully address this flexibility, a method for assessing the value of AM technologies in operations has to fulfill these four requirements:

- Production network level – not only one production line or factory but the whole production network
- Optimization – optimized network design
- Monetary evaluation criterion which covers flexibility – strategic investment decision with high investment costs and high impact on the company’s performance.

- Flexibility types – product mix, volume, and new product introduction flexibility

Siemens Industrial Turbomachinery uses AM for i) prototypes, ii) repair and iii) part production. AM is, in some cases, used to replace or complement existing traditional manufacturing methods. As an example, an advanced designed component having a number of internal features, previously manufactured in 14 separate steps, is today printed in one piece. The benefit with AM for this component is the dramatically shortened lead-time. Stratasys Ltd. and Siemens announced on November 16, 2016, a formal partnership to integrate Siemens' Digital Factory solutions with Stratasys' AM solutions. The companies laid the foundation to fulfill their vision of incorporating AM into the traditional manufacturing workflow, which can benefit multiple industries such as aerospace, automotive, transportation, energy and industrial tooling.

Sandvik Machining Solutions develops smart tools using AM. For certain components, there is not only a shortened lead-time, but also the fact that the 3D-printing can be cheaper compared to traditional methods. **Figure 21** shows an example of this. Another area is smart post-processing solutions applied to 3D-printed parts.

Figure 21 *Collector made in alloy 625 with PBF- EB by Sandvik*

In 2016 additive metal manufacturing began to grow in large manufacturing companies, and GE announced significant investments in the metal AM world. According to D. Scott [73], there are five industrial AM trends likely to be seen in 2017:

- Increased industrialization – companies like Additive Industries (MetalFAB1), EOS and Concept Laser are making automation systems to operate between machines, switching functions for each area in the production line. MetalFAB1 is also the only system to include a furnace for integrated stress relief heat treatment.
- Multimaterials, application-specific materials, and ceramics – nano-particle jetting process enables printing much more complex internal structures and supports.
- Broad adoption of AM for tooling – adoption of any manufacturing technology is driven by a product life cycle. GE said in 2016 that 25% of its products will be impacted by AM by 2020, meaning that AM can be used for tooling, or be used to make some smaller printed parts in a larger product.
- AM for small, complex, and expensive products – e.g. hearing aids, dental applications from aligners to crowns. These examples show the value of AM in the market. These products are still quite expensive but as more machines and additional materials become available prices are estimated to go down.

- Success through software – for AM to succeed it is essential that hardware, materials, and software are tightly aligned.

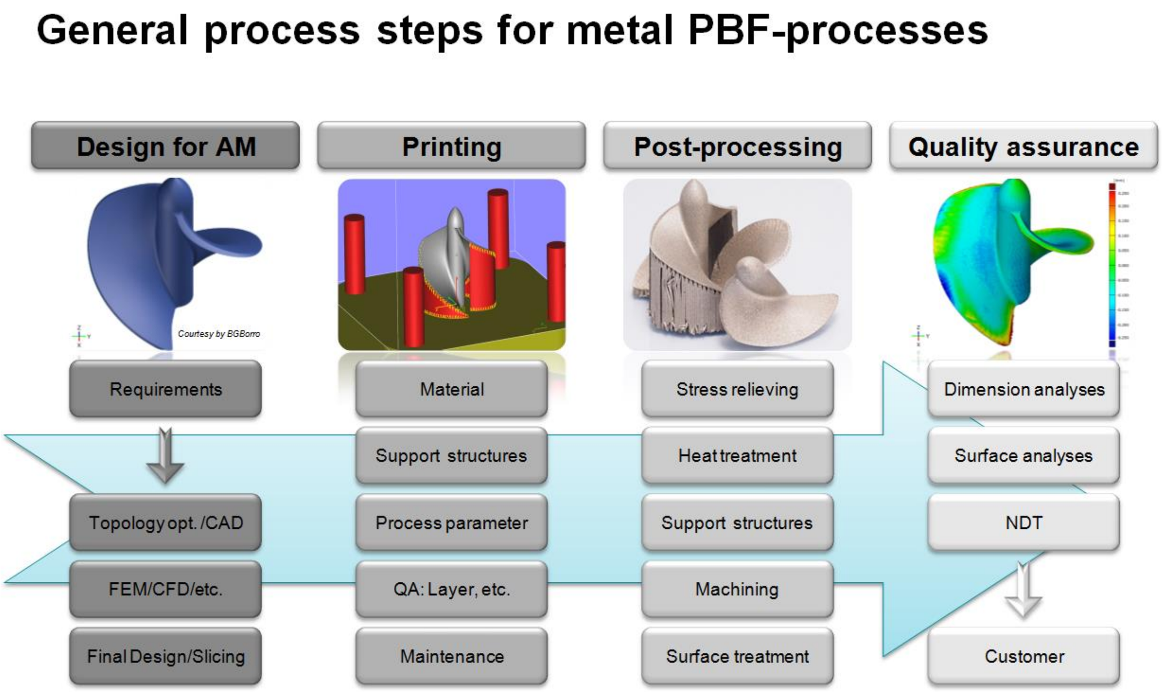

Figure 22 *General process steps for metal PBF-processes*

5.1.11. <u>Repair</u>

The first research on repair dates back to 1827 (Scopus), however, repair using Laser Metal Deposition (LMD) processes dates back to ~1970, **Figure 23**, with a boost in research by the beginning of 2000. LMD is one of the processes in the Directed Energy Deposition (DED) group.

Most of the research is carried out within the engineering and associated disciplines, **Figure 24**, and ILT in Fraunhofer seem to be most active in this area.

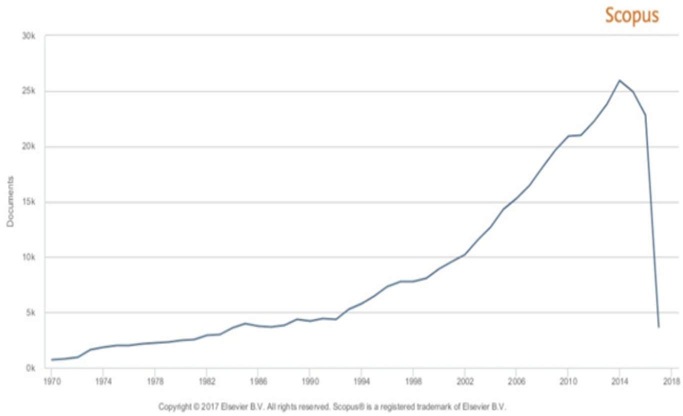

Figure 23 *Research documents on repair using LMD*

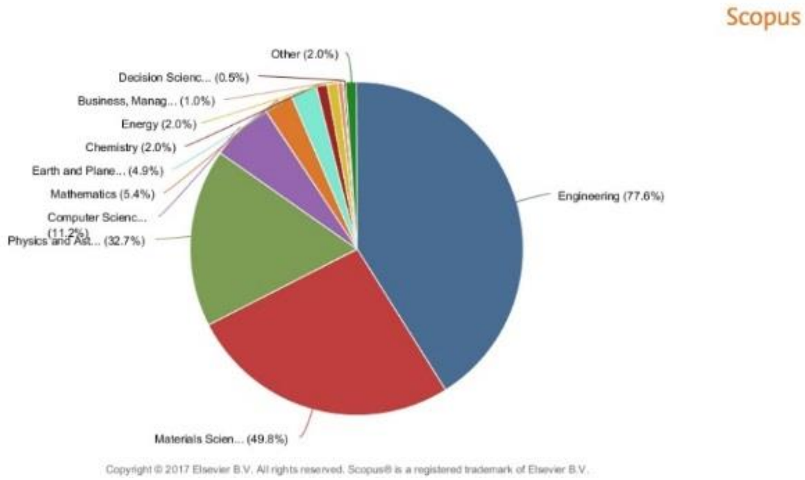

Figure 24 *LMD repair research as divided per discipline*

Looking at how the LMD repair work is divided by country, it can clearly be seen that it is driven by the US industry (**Figure 25**). It is also notable that the UK completely disappeared from the list by 2016.

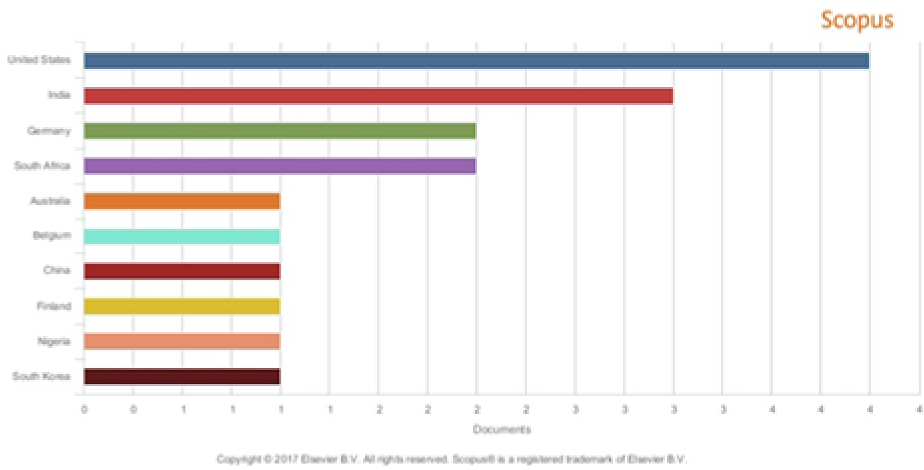

Figure 25 *LMD repair research as divided per country in 2016.*

Taking a closer look at the publications within “LMD and Repair” with respect to materials, it seems that the aerospace industry is driving the research, at least based on the type of materials that are easily extracted from the titles of the 198 different publications, see **Figure 26** below.

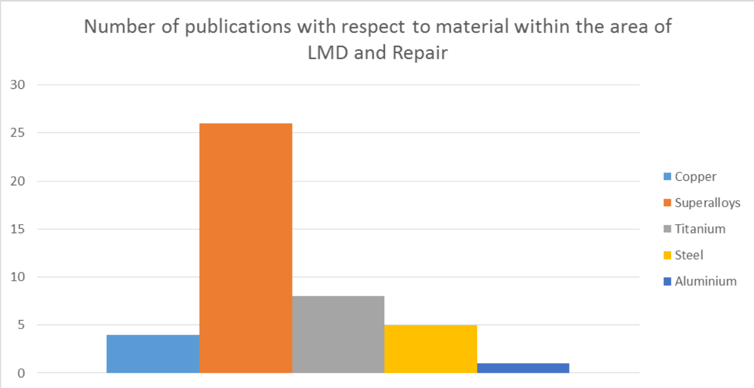

***Figure 26** The number of publications related to material within the field of “LMD and Repair”*

5.1.12. <u>AM as an enabling technology</u>

Even though AM still has its challenges, it has already proven its potential in some applications. The medical device industry was, for example, very early in adopting AM because of the possibility to produce customized components for patients. Besides the medical device industry, the aerospace industry has also realized that AM is a technology that has great potential.

Because of the way the AM processes works, it the enables completely new ways of thinking, in numerous ways including everything from geometrical design to material availability. Examples of products that were not possible to be manufactured with manufacturing technologies other than AM and that, today, are in commercial use include:

- **Acetabular cups with a special bone ingrowth surface** – a 3-dminesional lattice structure has been designed to promote bone ingrowth into a hip replacement implant. Without AM, it is not possible to produce the lattice structure needed and, from clinical trials, this has proven to be a successful structure to use. These acetabular cups are now in serial production with AM.
- **TiAl turbine blades** – TiAl is an intermetallic material which is very brittle and reactive due to its alloy content of almost 50 wt% of Ti and 50 wt% of Al. These properties make TiAl extremely difficult to process since the material is too brittle to be milled. It also extremely difficult to cast due to its reactivity. By using PBF-EB, that is run under vacuum, the material can be processed to near net shape, and is on the verge of hitting serial production. Without AM, the serial production of this material would not me possible.
- **Amorphous materials – thick sections** – Due to the local melting of materials with AM and the subsequent extremely fast cooling, AM enable amorphous metals to be produced. Production of thick sections of this kind of material had earlier been limited due to the lack of sufficient cooling speeds, but AM now enables them to be produced.

Figure 27 *A "hip cage" designed to support a patients weak bone. AM enables designers to use material and structures to tailor the flexibility of the cage to support the patient "just enough". Courtesy: AIM Sweden AB*

5.2. Social and economic state-of-the-art

5.2.1. IPR [74] [75] [76]

Figure 28 shows the number of AM-related patents issued (since 1995) and published (since 2001). Most of the patents concern technological advancements and a smaller number are design patents. Approximately 90% of these patents have been filed by the Aerospace and medical/dental industries. From lithium-ion batteries to human organs, the boundaries of additive manufacturing innovations are rapidly expanding. Traditionally reserved for industrial applications, additive manufacturing is creeping into mainstream and consumer use. With larger scale adoption comes a significant increase in IP disputes among those seeking to benefit from this transformative technology. To survive these inevitable clashes over valuable IP assets, rights holders need to understand the relevant, complex, and rapidly-evolving legal landscape, including the multiple opportunities and pitfalls. Vogels article reviews the advantages and limitations of legal strategies used to create, protect, attack, and defend stakeholders' IP in this burgeoning field. A full industrial 3D-printing system will typically touch upon various intellectual property rights; patent rights of 3D printing components, processes and raw printing material, trade secret protection of 3D printing manufacturing processes, copyright protection of controlling software programs, design protection of 3D object designs, and trademark protection for the 3D printer itself. Patents concerning equipment dominate followed by patents connected to materials and products (**Figure 29**).

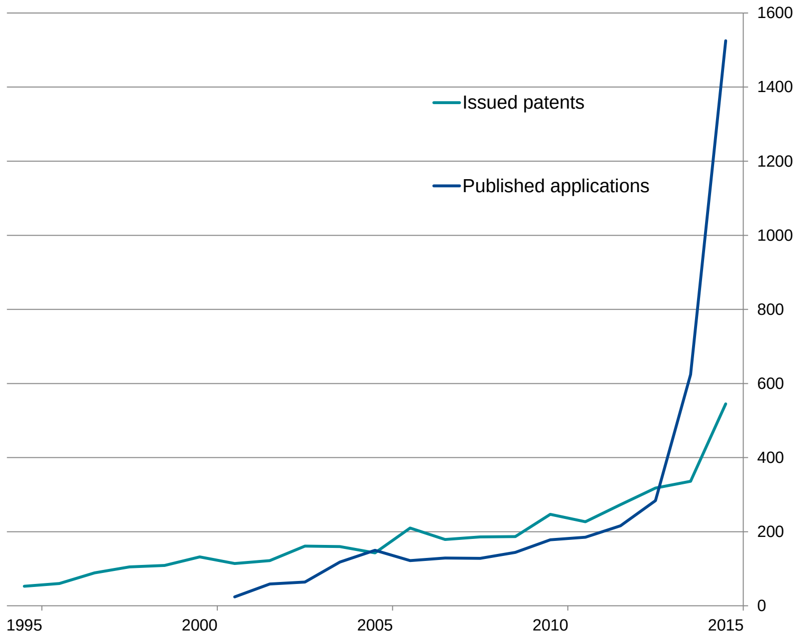

Figure 28 *Issued (since 1995) and published (since 2001) AM-related patents (from Finnegan, Henderson, Farabow, Garret & Dunner LLP)*

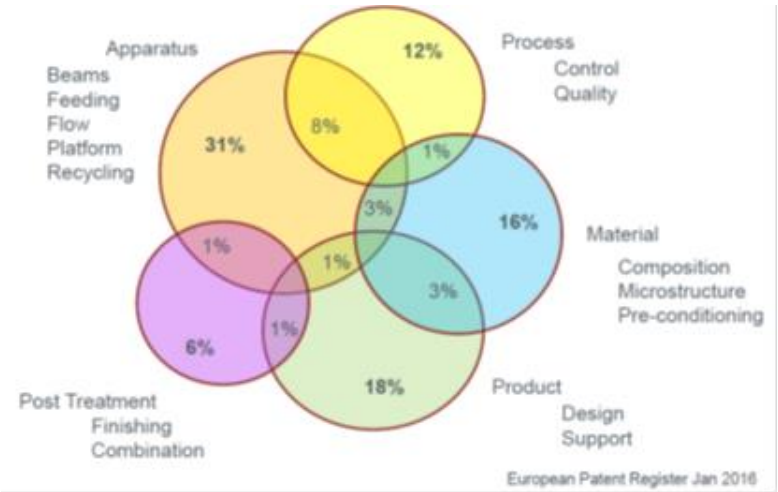

Figure 29 *The graph shows that patents concerning equipment dominate followed by patents connected to materials and products. Source: Ceulemans, J. "Patenting Behaviour in Metal Additive Manufacturing", presented at WorldPM2016, Hamburg, Oct.9-13, 2016*

5.2.2. <u>Standards & certification [77] [78]</u>

The ASTM International Committee F42 was established in 2009 and has formulated its scope as "The promotion of knowledge, stimulation of research and implementation of technology through the development of standards for additive manufacturing technologies". F42 has today more than 400 individual members from approximately 25 countries.

ISO Technical Committee 261 (ISO/TC 261) was established in October 2011 after an initiative from DIN, based on VDI Guidelines in "Rapid Technologies". The scope for ISO/TC 261 is "Standardization in the field of Additive Manufacturing (AM) concerning their processes, terms and definitions, process chains (Hard- and Software), test procedures, quality parameters, supply agreements and all kind of fundamentals". Membership is based on representation from national standardization organizations, like SIS, and each organization has 1 vote. Today, ISO/TC 261 consists of 21 member countries and 7 observers. Each member organization may nominate experts for different workgroups.

ISO and ASTM signed in July 2013 a partnership agreement for a joint development of AM standards following guiding principles as

- One set of AM standards – to be used worldwide
- Common roadmap and organizational structure for AM standards
- Use and build upon existing standards, modified for AM when necessary
- For efficiency and effectiveness, ISO/TC 261 and ASTM F42 should begin the work together and in the same direction
- Emphasis on joint standards development
- Start with the most urgent terms
- First jointly developed ISO & ASTM standard is 52900 – Terminology, which is based on two existing standards on terminology; F2792-12a and ISO 17296-1

The standardization committees have agreed on a three level AM standards structure.

1. General top-level standards (general concepts, common requirements, generally applicable).
2. Category AM standards (specific to material category or process category) and involving standards for feedstock materials, process/equipment and finished parts.
3. Specialized AM standards (specific to material, process, or application).

In July 2015 CEN/TC 438 was formed with the aim to transform ASTM/ISO standards to CEN standards & European standards).

In Sweden SIS has formed SIS/TK 563 with the aim to ensure Swedish interests by following and actively taking part in the development of AM standards. This is done by nomination of experts to various working groups. Acting as the leader of ISO/TC 261/WG1 Terminology, Sweden has taken a strategic and important role in the work. Presently, TK 563 has 10 members representing both companies as well as academia and has nominated experts or is active in other ways in 7 international working-groups. Members March 2017: Alfred Nobel Science Park, Arcam AB, Carpenter Powder Products AB, Electro Optical Systems Nordic AB (EOS), Höganäs AB, RISE Mätteknik, AB Sandvik Materials Technology, Siemens Industrial Turbomachinery, Swerea AB, Volvo Car group.

Examples of recently published AM related standards can be found in **Appendix 9**. The content of Swedish standards (SS-EN ISO/ASTM xx) are identical with the originally published ISO/ASTM xx or ISO xx standards with the same number but with a different year of publication. Recently, ISO/TC/WG1 initiated a revision of ISO/ASTM 52900 and the goal is to present a revised version by the end of 2017. Abbreviations of the 7 process categories together with a guide to further precision of sub categories and materials is planned to be added in the revised standard.

The SASAM project1 presented a roadmap for standardization of AM and Aumund-Kopp2 gives an overview of standards relevant for additive manufacturing.

5.2.3. Education & training [79]

AM is currently very well covered by media and hence is exciting curiosity in the student environment. On the other hand, there is strong demand from the industry globally, as well as in Sweden, in engineers and designers with a focus on AM. This results in a booming number of AM courses at the bachelor and master level at universities around the globe, and courses that include AM or 3D printing can now be found at most of the universities. The significant decrease in the price of the desktop 3D printers has resulted in the utilization of additive manufacturing in a number of design courses, from engineering design to art and industrial design.
AM is widely integrated into conventional undergraduate and graduate programs, as well as specialized AM courses that are being proposed and developed at universities around the world as part of engineering, technology and design curricula. They include Pennsylvania State University, Clemson University, National American University, Colorado State University, University of Colorado, the University of Nottingham, Loughborough University, Politecnico di Torino, etc.

Swedish universities are either already including AM in the education or are planning to do so in the near future. Chalmers, for example, is actively working in this direction and has, in January 2017, started an annual MSc course on AM "*MTT120 "Additive Manufacturing*"[1]. AM is also integrated in a number of bachelor courses at Chalmers in the industrial economy and mechanical design programs with a total of about 200 students per year. Chalmers will also start a new bachelor course on additive manufacturing "*MTT125 "Additive Manufacturing*".

Örebro University together with University West and Mid Sweden University are giving PhD course in the frame of Production 2030. Örebro University also holds doctoral seminars on different locations around Sweden about the impact of 3D printing of metallic materials on business development, business models, value chains, product development, production systems, etc. Shorter courses in design for AM are given at Lund University and Örebro University, and are intended for both industry and academia.

Educational programs for operators of equipment and 3D-printing specialists are given at a number of university colleges in Sweden such as, for example, Xenter, Eslöv and Nackademin.

5.2.4. Liability

Where a product is manufactured through AM, the line of responsibility becomes less clear. Small businesses and entrepreneurs without the traditional resources will now be producing goods – with significantly reduced costs of market entry but, at the same time, bringing with them the risk of less attention being paid to product design and quality assurance – and this may prove a headache for regulators.

* internet sellers only offering product designs for download are likely to disclaim responsibility for their safety, arguing that their activities do not impact on the safety of the product, and direct regulators to the designer.

* the designer may be an individual or small business lacking the necessary resources to meet consumer compensation claims, undertake a timely recall campaign, manage calls from affected customers or handle the logistics of replacing affected products.

* there is an increasing risk that unsafe consumer products will not be identified at an early stage.

The difficulties of determining where responsibility for product defects lies will increase. Ultimately, the allocation of liability through the supply chain will often be determined by contractual arrangements. However, the strict liability regime established under the product liability Directive (85/374/EEC) (PLD) is likely to remain an important route for personal injury claims arising from product safety defects. The PLD places liability on the producer for defects giving rise to the injury.

Clarification will be needed as to how products should be considered by the producer where, for example, the product file has been corrupted as a result of the uploading/downloading process, or where a defect relates to the materials used in the printing process, problems with the printer or other factors such as the temperature or atmospheric conditions in which the printing takes place.

Warnings and instructions will take on even greater importance as the design and manufacturing processes become divorced, and printing is increasingly undertaken by individual end users. Prudent designers will need to ensure that detailed manufacturing instructions, guidance on suitable materials and adequate warnings are provided to those printing their designs to defend claims brought under the PLD.

The draft standard ASTM/ISO 52901.2:2016 covers the definition and communication of requirements for purchased parts made by AM. The standard is intended to be used by part providers and/or customers of parts made by AM. The standard specifies guidance for the elements to be exchanged at the time of order; including customer order information, part definition data, raw material requirements, final part characteristics and properties, inspection requirements, and part acceptance methods. It is a top-level standard in that it is intended to apply to parts made by any AM process and any material type. It is recommended that the document is used as a basis for obtaining parts made by AM to meet minimum acceptance requirements and that more stringent part requirements shall be specified through addition of one or more supplementary requirements.

5.2.5. Need for new business models [80] [81]

Markets for AM could be characterized by four patterns:

- Small production output; prototyping, spare parts for older product families
- High product complexity; lightweight constructions in the aerospace or performance car industries, product design where current production technologies cannot provide complicated internal structures
- High demand for product customization tailored to individual customer’s needs; typical for many medical or dental applications, consumer market like jewelry or sport performance products

- Spatially remote demand for products; decentralized production of spare parts in the mining industry or on exploitation platforms in the oil industry

Table 5 *3D printing – Key Transformational Shifts (information from https://www.slideshare.net/JacekDukat/additive-manufacturing-2016)*

Mass production to Mass customization		
Smaller batches of production with high levels of customization		Lower throughput compared to traditional manufacturing. But faster time to market
Supply chain focus: from "Push" to "Pull"		
Demand happens parallel to production		Demand supersedes production
Forecasted demand to Real-time demand		
To document, relay and realize demand in real-time		Eliminates the need to store finished products based on forecasted demand: lesser storage space required
Inventory: Finished products to Raw materials		
Manufacturers will store only the raw materials to meet on-demand production requirements		Low-storage space requirements as raw materials occupy lesser volume than finished products
Manufacturing: Global to Local		
Hub and spoke model of supply chain will be challenged. Hubs will lose importance		Global production houses will lose the competition to local manufacturing centers

Key 3D-printing business models:

- In-house 3d printing; The manufacturing company has the in-house capability to 3D-print components
- Contract based manufacturing; The manufacturing company outsources its work to a 3D printing company
- 3D printing service; Clients place their order or design desired products online on the 3D printing companies website

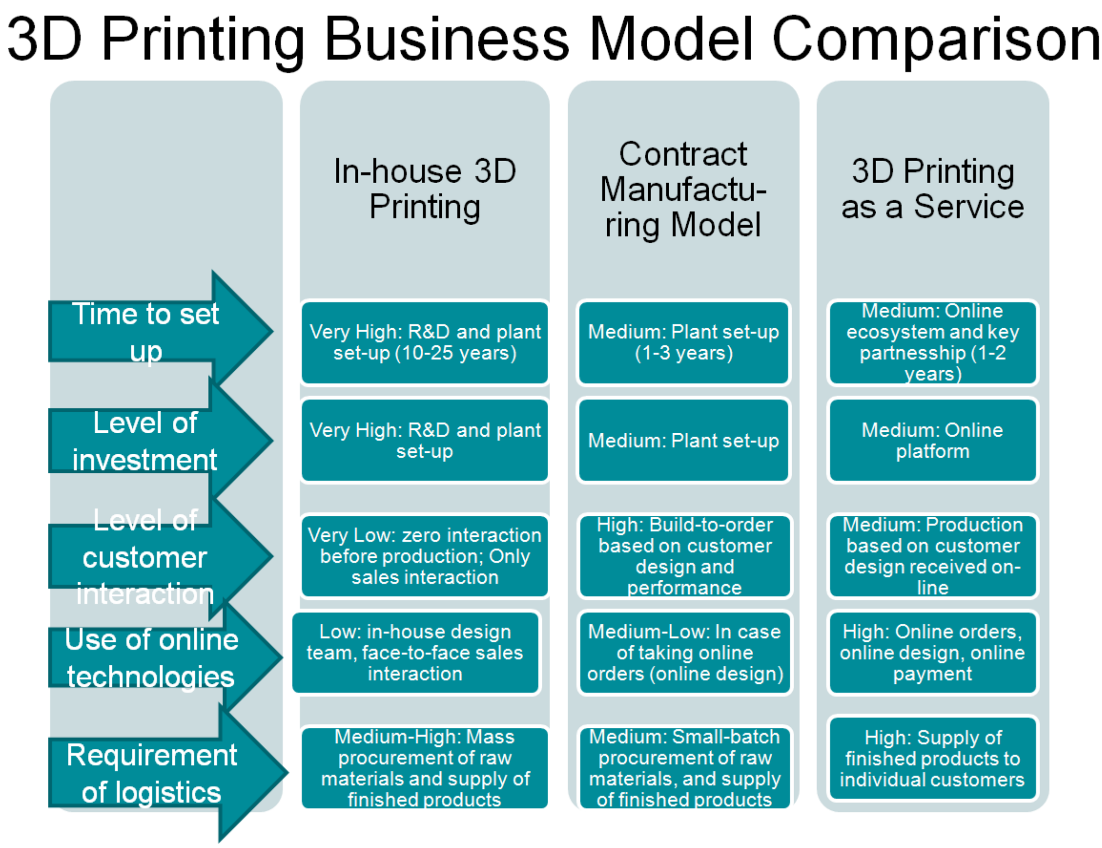

Figure 30 *3D-printing business model comparison (information from https://www.slideshare.net/JacekDukat/additive-manufacturing-2016)*

5.2.6. Environmental impact, LCA/recycling [82] [83] [84] [85] [86]

Kerbrat presents, in addition to a literature review, a methodology for environmental impact assessment. The method considers the part's design and machine technology and is divided into 3 steps; raw material preparation impact, process impact, and lost material recycling impact.

Specific Energy Consumption in kWh/kg has been used to compare the environmental impact of different manufacturing processes due to each ones electric consumption. The morphology of the parts produced as well as its position and orientation in the machine space have strong influences on the result. It is difficult to consider which process has the less environmental impact as the processes do not allow production of parts with identical specifications. For example, SLA machines produce prototypes whose lifetime is limited while PBF-LB or PBF-EB will realize functional parts whose lifetime is expected to be much longer.

Application to directed energy deposition – CLAD-process – for a machine having 2 nozzles, MesoCLAD and MacroCLAD, respectively and taking into account electrical consumption, material consumption and fluids consumption (water and gas) and applied on manufacturing of a box-like part 208 x 208 x 84 mm outer dimensions and wall thickness 4 mm. In this case the MacroCLAD nozzle resulted in the lowest environmental units (mPts) mainly because of a much shorter building time and a higher efficiency resulting in less powder consumption.

Frazier notes, in his review paper (2014), a few studies on the state-of-the-art of environmental impact of AM. He mentions that the ATKINS project (2007) concluded that an optimal design could show a weight and material saving of almost 40%. As an example: reducing the weight of a long range aircraft by 100 kg results in both a 2.5 MUS$ saving in fuel and a 1.4 $MtCO_2$ savings over the lifetime of the aircraft. Frazier concludes that more work needs to be done to investigate the impact of AM on the environment.

5.2.7. Health, safety and environment

Health, safety and environmental concerns around AM have been raised over the last few years as the industry has grown [23]. In the United States, the FDA's Department of Health and Human Services Justifications of Estimates and Committee started work during 2015 to identify standards and regulations regarding metal AM fabrication. Also North West University and the South Africa's Department of Science and Technology, in South Africa, are also looking at health and safety aspects with AM fabrication.

AM is usually stated to be an environmentally friendly process since material waste is minimized and that the process is very efficient. However, the environmental risks are not yet fully understood as energy is consumed to produce metal powder, and the metal powder itself has risks for health, safety and environment. Examples of this include (Based on [87] [88] [89]):

- Be aware of formation of dusts, not only close to the 3D-printer but also in other areas in the workshop where, e.g., post-processing operations are performed
- Cobalt, chromium, nickel and other carcinogen or allergenic species, fine metal dusts may be ignitable or explosive
- It can be difficult to remove all the fine metal powder particles from a printed component. Careful cleaning is required before the part is transported to another department outside the 3D-printing work-shop
- A section on "Safety and Environment" is included in VDI 3405 but otherwise not addressed by the currently published standards on AM
- A systematic AM safety management plan can provide a framework for identifying potential risks and developing strategies or eliminate their impact.

In Sweden a project hosted by Linköpings Universitet and funded by AFA Försäkring called "Hälsoeffekter vid professionellt arbete med 3D-skrivare" is investigating the health and safety aspects of metal AM [90]. To date, this is the only ongoing project in this matter in Sweden. However, the concerns about health and environment around plastic and metal AM have been raised by the association for Swedish Water and reported in a debate article that they have found hazardous traces originating from users of AM [91]. The Swedish Association for Additive Manufacturing (SVEAT) has taken these questions to their members to investigate this area in Sweden.

6. Challenges

Different challenges have been described throughout this report and some major challenges are summarized below divided into general challenges and technical challenges.

6.1. General challenges

Many large Swedish corporations are owned by foreign organizations. Why should Swedish companies and production stay in Sweden? How can competence and jobs be kept in Sweden? Close collaboration with universities and institutes, with strong research within AM and good education, could be one motivation for the companies to stay in Sweden. Could an even more innovative environment be created in Sweden to attract industry?

There is a lack of people with education and experience of AM. Especially design engineers would need more education to design for AM and not for conventional manufacturing.

6.2. Technical challenges

Throughout this report, challenges are listed for different stakeholders and different technical areas. Some of the major challenges to industrialize AM of metals more widely are the robustness of the process, qualification, productivity, post processing, surface finish, automation, digitalization and cost. Also, a lack of materials and standards slows down the industrialization. Additionally, more widespread knowledge about design for AM would be needed to use AM to its full potential.

In the next stage of the project RAMP-UP, the focus will be on identifying the most important challenges and research questions for Sweden to focus on, in order to speed up the industrialization of AM of metals. Based on the Swedish competence within materials and powder, we should be able to contribute to solving challenges like the lack of materials, lack of suitable powder characterization methods and recycling of powders. The same applies to the challenges involving automation and digitalization.

7. Opportunities – Swedish areas of excellence

In order to support the industrialization of AM of metals in the most efficient way, it needs to be based on the already existing strengths and industry in Sweden. As Sweden is a small country, a focused effort will be needed. To try to do everything will not give Sweden any cutting edge advantage and international leadership.

Some areas have been identified and highlighted as possible areas to build on for AM of metals and they are described below. They are in line with the areas identified by Johan Harvard at the National Innovation Council leading the government's strategic innovation partnership programme "A connected industry and new materials".

Swedish industries have a tradition for niche products with high values and in which a high level of technology are integrated. These product types are well suited to additive manufacturing, as AM has the potential to add value to the product and its system. Value addition can come from i.e. innovative design, part consolidation, tailoring of materials, and a more sustainable manufacturing.

The most essential building blocks are in place in Sweden through a strong primary industry, the world's leading automation companies, leading IT and telecom companies, a lot of system expertise, excellent research and industry in materials, high environmental awareness and innovative young companies at the digitization forefront. (Presentation at SIP Metallic Materials conference 2017-03-07, https://www.youtube.com/watch?v=fIhMerjXN_k).

7.1. Material and powder industry and expertise

Sweden has a long tradition of iron and steel and is producing 4.6 Mton of steel per year, compared to the world production of 1 629 Mton. The Swedish steel companies are highly specialized and often world leaders in their respective product areas. Powder metallurgy is one example where the Swedish powder producers have approximately 25% of the world market of metal powder.

Another part of powder metallurgy is cemented carbide, with a long history, starting with lamps (Osram in Germany and Luma in Sweden) and evolving to tools for metal cutting and rock drilling.

This strong industry has led to deep knowledge within materials research and development, both for metal and powder at Swedish universities and institutes. One example tool for alloy development includes thermodynamic and kinetic calculations, resulting in the spin-off company Thermocalc from KTH. Other newly formed Swedish material companies within AM include VBN Components, Exmet, Metasphere and Freemelt.

For non-ferrous metals, copper and silver mines existed in Sweden, but the main industry today is with processing of Aluminium and Brass alloys. Sweden has a long tradition in metallic materials for the dental and medical device segments. Professor Brånemark discovered the phenomenon of osseointegration, where bone cells anchor to a metallic surface. This discovery led to great success in Sweden with extensive research in materials for dental and medical devices where new types of materials and surface treatments where developed and commercialized. Swedish material suppliers have also been active in the development, production and sales of materials for the medical sector. This strength can be utilized to promote the material Sweden produces by tailoring materials for the medical device industry.

7.2. Manufacturing industry and expertise

The manufacturing industry in Sweden is competitive with a large part of customer-specific and high-end goods, niche products and services. The industry segments include e.g. automotive, aerospace, tooling, energy, process and engineering industry and the list of companies is very long. Likewise, equipment suppliers like Arcam and Digital Metal for AM of metals and Quintus Technologies for hot isostatic presses are unique in their field. These competences are seen as a strength for Sweden and its industries and most certainly applicable for AM industrialization.

7.3. Digitalization and automation

Sweden has a long tradition of automation, being a leading nation, and Sweden also has a strong position regarding IT and digitalization. For AM applications work in this field has already started and one example is the pilot project DINA (Dnr: 2016-01968). The project has had, as one of the deliverables, a RoadMap in the field of digitalization for production of AM components. The short list of activities for a future of easy production of AM components is:

- **Agile product creation**
    - ↘ New tools that rapidly include customers changing needs in product functionality, production volumes and circular flows already in the design phase.
- **Seamless data flows in the digital manufacturing chain**
    - ↘ All engineering and manufacturing methods and tools are seamlessly integrated with well-defined interfaces and total interoperability.
- **Adaptable planning and production**
    - ↘ Full control the whole manufacturing route. All functions in the production chain are ready and in time by optimized manufacturing planning. All resources are continuously on-line; workshops, suppliers, logistics and order situations.
- **Total process control, information feedback and forward**
    - ↘ The AM process, be it PBF-EB, PBF-LB, WDED is correctly executed. The control of the process is aided by relevant monitoring. All information from the monitoring and process control is accessible for control of subsequent steps and for analysis.
- **Quality by traceability and analysis of data**
    - ↘ The quality of the component is assured by the delivered data. The data is also statistically analyzed for feedback to the planning and control of the production chain and AM process itself.
- **Knowledge generation and education**
    - ↘ The lack of knowledge and stilled staff reduces the possible rate of evolution. Generating new knowledge and build an education system for production of AM components will rapidly improve the applicability of AM production.

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Swerea IVF
Chalmers
Högskolan Väst
Swerea SWECAST
KTH

Arcam AB
Carpenter Powder Products AB
Construction Tools PV AB
Höganäs AB
Quintus Technologies AB
Saab AB
AB Sandvik Machining Solutions
Scania CV AB
Siemens Industrial Turbomachinery AB
Uddeholm AB

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III. Appendix 1

(AUS) Additive Manufacturing Technology Roadmap for Australia (2011)

(EU) Additive Manufacturing Strategic Research Agenda (2014)
(EU) Additive Manufacturing: SASAM Standardisation Roadmap (2014)
(EU) Additive Manufacturing in FP7 and Horizon 2020 (2014)
(EU) AM for competitive and sustainable economy (CECIMO) (2015)
(EU) Additive Manufacturing and 3D-Printing Technologies in the EC (2016)
(EU) Additive manufacturing roadmap: gaps and actions on market driven value chains (2016)
(EU) Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing (3D-printing) (2016)

(GER) DMRC Study Part 1 Analysis of promising industries (2011)
(GER) DMRC Study Part 2 Future applications (2012)
(GER) DMRC Study Part 3 innovation Roadmapping of Required Advancements (2013)
(GER) DMRC Study Part 4 Exploring the Research Landscape (2013)
(GER) DMRC report Annual 2015
(GER) Research in Germany Manufacturing Sciences and Engineering (2016)

(JPN) The current status and outlook for additive manufacturing in Japan (2016)

(SWE) Effektanalys, strategiska utvecklingsområden för svensk tillverkningsindustri (2010)
(SWE) COMING TOGETHER TO LEAD THE WAY - A Swedish Agenda for Research and Innovation within Additive Manufacturing and 3D printing (2014)
(SWE) 3d printing - economic and public policy implications (2014)
(SWE) Smart industry – a strategy for new industrialisation for Sweden (2016)
(SWE) Mapping of AM projects at Vinnova (2016)
(SWE) The Adoption of Additive Manufacturing Technology in Sweden (2016)

(UK) East Midlands rapid manufacturing Strategy-moving towards 2020 (2008)
(UK) EPSRC Centre for Innovative Manufacturing in Additive Manufacturing, Annual report 2012
(UK) Shaping our National Competency in Additive Manufacturing in UK (2012)
(UK) Additive Manufacturing education in the UK (2012)
(UK) UK-AM-National-Strategy-Update-Report-1.2 (2015)
(UK) UK-AM-National-Strategy-Update-Report-2.2 (2015)
(UK) UK-AM-National-Strategy-Update-Report-3-v2 (2016)
(UK) The Current Status and Impact of 3D Printing Within the Industrial Sector: An Analysis of Six Case Studies (2015)
(UK) Additive Manufacturing in UK (2016)
(UK) Mapping UK Research and Innovation in Additive manufacturing (2016)

(USA) The U.S. Advanced manufacturing initiative: Federal resources and opportunities for Public/Private Partnership (2011)
(USA) Ensuring American Leadership in Advanced Manufacturing (2011)
(USA) CAPTURING A DOMESTIC COMPETITIVE ADVANTAGE IN AM (2012)
Annex 1: Technology development
Annex 2: Shared infrastructure and facilities
Annex 3: Education and Workforce Development
Annex 4: Policy
Annex 5: Outreach

Annex 6: Regional meeting summaries

(USA) Measurement Science for Metal-Based Additive Manufacturing (2013)
(USA) Designing a Digital Future: Federally Funded Research and Development in Networking and Information technology (2013)
(USA) Nondestructive Evaluation of Additive Manufacturing (2014)
(USA) The future of 3-D printing: Moving beyond prototyping to finished products (2014)
(USA) U.S. National Strategy for Additive Manufacturing (2014)
(USA) Workforce of the future Advanced manufacturing's impact on the global economy (2016)
(USA) Additive Manufacturing in Aerospace, Defence & Space – Trends and Analysis (2016)
(USA) Policy needed for additive manufacturing, Nature Materials, vol 15 August (2016)

(Others) Disruptive technologies: Advances that will transform life, business, and the global economy (2013)
(Other) ESA, Additive Manufacturing Roadmap, Issue 1 rev. 2 (2015)
(Other) Rapid prototyping in Europe and Japan Vol 1 (1997)

IV. Appendix 2

Mergers and acquisitions 2013

- 3D Systems acquired software supplier Geomagic for €41 M
- 3D Systems acquired Phenix for €17 M
- Stratasys acquired Makerbot for €303 M
- Groupe Gorgé acquired Prodways Group

Mergers and acquisitions 2014

- RTI International Metals acquired Directed Manufacturing, for €19 M.
- Arcam acquired powder producer AP&C for €14 M
- Trumpf and Sisma Joint venture. Acquired SpaceClaim by Ansys, €64 M
- Autodesk acquired Within Technologies for €65 M
- 3D Systems acquired Layerwise for €32 M
- Arcam acquired DiSanto
- Stratasys acquired Solid Concepts and Harvest Technologies, and will combine Solid Concepts and Harvest Technologies with RedEye.

Mergers and acquisitions 2015

- 3D Systems acquired CAD/CAM software provider Cimatron for €88 M
- H.C. Starck acquired powder producer Metasphere
- Global Tungsten & Powders acquired powder producer Tikomet
- Autodesk acquired Netfabb for €38 M
- Gorgé Group acquires INITIAL and NORGE Systems

Mergers and acquisitions 2016

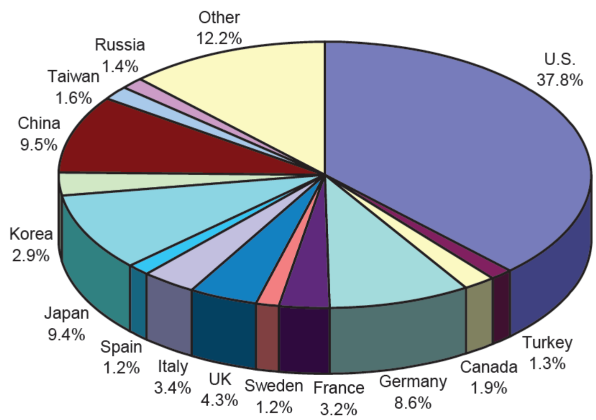
- Moog Inc acquired 70% of Linear Mold and Engineering
- Heraeus and Exmet form a partnership to develop amorphous metals
- Siemens acquired 85% of service provider Material Solutions
- Concept Laser form partnership with Swisslog to develop AGV
- Oerlicon acquired design and service provider Citim
- GE acquired 75% stake in Concept Laser for €551 M
- GE acquired 76% stake in Arcam for €596 M

Mergers and acquisitions 2017

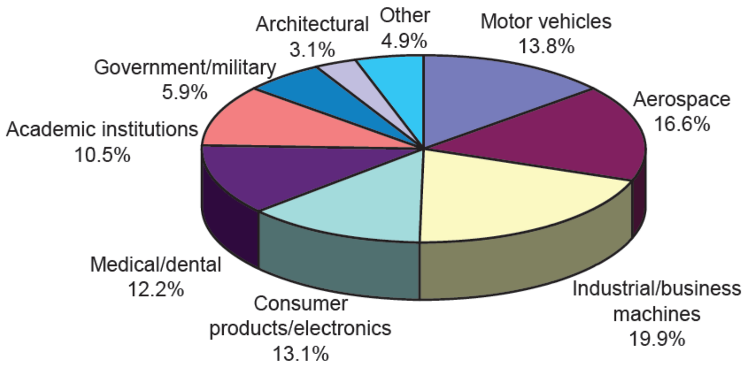
- DMG MORI AG acquires 50,1% shares in REALIZER GmbH.
- atum3D announced an extensive partnership with 3D Center
- Stanford Marsh Group acquires Tri-Tech 3D.
- Carpenter to acquire titanium 3D printing powder firm, Puris for €30 M.

V. Appendix 3

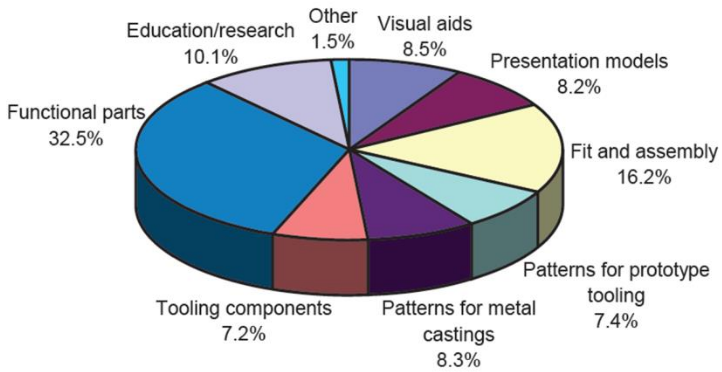
Investments in equipment according to Wohlers report 2016.



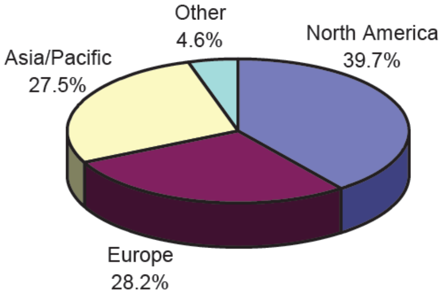
Investment in equipment 2015 split on Countries, according to Wohlers report 2016



Investment in equipment 2015 split on branches, according to Wohlers report 2016



Investments split on applications, according to Wohlers report 2016.



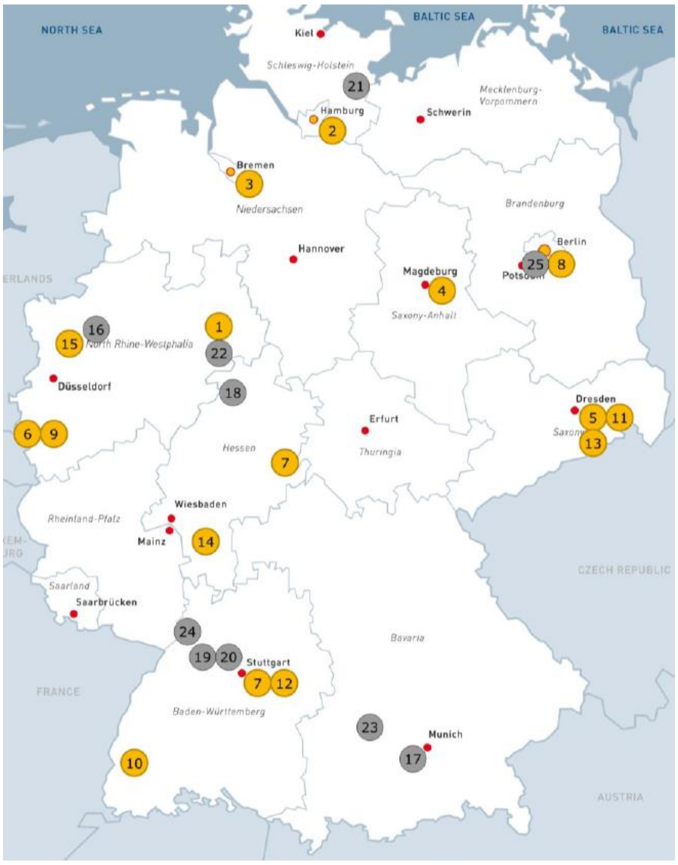
Accumulative number of equipment split on regions until 2015, according to Wohlers report 2016

VI. Appendix 4

Currently there exist over 10 large research groups and companies in China involved in AM research:

- Northwestern Polytechnical University
- Beihang University
- South China University of Technology
- Nanjing University of Aeronautics and Astronautics,
- University of Science and Technology of China,
- Shanghai Jiao Tong University,
- Northwest Institute for Nonferrous Metal Research,
- China Academy of Engineering Physics
- Beijing Longyuan
- Tsinghua university,
- Huazhong University of Science and Technology
- Xi'an Jiao Tong University.

VII. Appendix 5



Selected Additive Manufacturing / 3D Printing Players in Germany

1	Direct Manufacturing Research Center (DMRC)	Paderborn
2	Laser Zentrum Nord	Hamburg
3	Fraunhofer for Manufacturing Technology and Adv. Materials IFAM	Bremen
4	Fraunhofer for Factory Operation and Automation IFF	Magdeburg
5	Fraunhofer for Ceramic Technologies and Systems IKTS	Dresden
6	Fraunhofer for Laser Technology ILT	Aachen
7	Fraunhofer for Manufacturing Engineering and Automation IPA	Stuttgart
8	Fraunhofer for Production Systems and Design Technology IPK	Berlin
9	Fraunhofer for Production Techno-logy IPT	Aachen
10	Fraunhofer for Mechanics of Materials IWM	Freiburg
11	Fraunhofer for Machine Tools and Forming Technology IWU	Dresden
12	Fraunhofer for Industrial Enginee-ring IAO	Stuttgart
13	Fraunhofer for Material and Beam Technology IWS	Dresden
14	Fraunhofer for Computer Graphics Research IGD	Darmstadt
15	Fraunhofer for Environmental, Safety and Energy Technology UMSICHT	Oberhausen
16	Envisiontec	Gladbeck
17	EOS Electro Optical Systems	Krailing / München
18	Concept Laser	Lichtenfels
19	Rapid Shape	Heimsheim
20	Trumpf	Ditzingen
21	SLM Solutions	Lübeck

22	Realizer	Borchen
23	Voxeljet	Friedberg
24	Nanoscribe	Eggenstein-Leopoldshafen
25	BigRep	Berlin

VIII. Appendix 6

Most of the nationally funded research projects in Sweden within AM and metals with start date from 2011 are listed below.

2011:

- Plattform för direkttillverkning av mikrokomponenter
  http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2009-03261/Plattform-for-direkttillverkning-av-mikrokomponenter/

2012:

- Systematiserad prototypframtagning för ökad konkurrenskraft (SPÖK)
  http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2009-03261/Systematiserad-prototypframtagning-for-okad-konkurrenskraft-SPOK/
- Additiv tillverkning av fordonskomponenter
  http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2009-02186/Additiv-tillverkning-av-fordonskomponenter/

2013:

- Additivt tillverkade verktyg för skärande bearbetning
  http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2009-02186/Additivt-tillverkade-verktyg-for-skarande-bearbetning/
- Tribologiskprovning av additivt tillverkat material för bränsleventil
  http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2009-02172/Tribologisk-provning-av-additivt-tillverkat-material-for-bransleventil/
- COMING TOGETHER TO LEAD THE WAY-a Swedish agenda for research and innovation within additive manufacturing and 3Db printing.
  http://www.er.umu.se/digitalAssets/153/153175_vinnova_swedishagenda_additivemanufacturing3dprinting_2014.pdf

2014:

- Optimerad produktionsprocess för additiv tillverkning (OPTIPAM)
  http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2014-00600/Optimerad-produktionsprocess-for-additiv-tillverkning/
- Nya generationens verktyg genom additiv tillverkning (ADDING)
  http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2014-00597/Nya-generationens-verktyg-genom-additiv-tillverkning-ADDING/
- Innovativ komponentteknologi via pulverteknik
  http://www.vinnova.se/sv/Resultat/Projekt/Effekta/Innovativ-komponentteknologi-via-pulverteknik/
- Optimerad produktion av små metalliska komponenter med PBF-EB-teknik

2015:

- Additiv tillverkning: Skadetålighet hos flygkritiska artiklar
  http://stratresearch.se/en/research/ongoing-research/industrial-phd-2014/project/6881/
- Högpresterande lättviktskomponenter genom additiv tillverkning
  http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2014-00596/Hogpresterande-lattviktskomponenter-genom-additiv-tillverkning/
- Pulver och materialdesign för flexibel additiv tillverkning av högpresterande komponenter

http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2014-00597/Pulver-och-materialdesign-for-flexibel-addtiv-tillverkning-av-hogpresterande-komponenter/

- Demonstration of additive manufacturing as a method for fabrication of 316L-Grade Components https://www.miun.se/sports-tech-research-centre/forskning/pagaende-projekt/demonstration-of-additive-manufacturing-as-a-method-for-fabrication-of-316l-grade-components/
- Additiv tillverkning med pulver som tillsatsmaterial http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2014-04016/Additiv-tillverkning-med-pulver-som-tillsatsmaterial/
- Utveckling av nästa generations verktyg genom additiv tillverkning -Steg 2 (ADDING II) http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2014-00597/Utveckling-av-nasta-generations-verktyg-genom-additiv-tillverkning---Steg-2/
- 3D Nano-plattform
- Modelleringsstödd materialutveckling för Additiv Tillverkning av nya Pulverstål http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2014-00597/Modelleringsstodd-Materialutveckling-for-Additiv-Tillverkning-och-nya-Pulverstal/
- Utvärdering av metod för gjutinfiltrering av järnpulver (P-cast). http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2014-00597/Utvardering-av-metod-for-gjutinfiltrering-av-jarnpulver-P-cast/
- Kompetensutveckling inom optimering av PBF-EB-teknologin http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2014-00600/Kompetensutveckling-inom-optimering-av-EBM-teknologin/
- AM-Pulverbädd
- ROBIN (AM/Svets Auto)

2016:

- Utveckling av processer och material i additiv tillverkning http://stratresearch.se/en/research/ongoing-research/generic-methods-and-tools-for-production-2014/project/7143/
- Matematik för elektronstrålesmältning: 3D-skrivning I metal

http://stratresearch.se/en/research/ongoing-research/industrial-phd-2015/project/7504/

- Laserbaserade 3D printning och processing

http://stratresearch.se/en/research/ongoing-research/materials-science-2015/project/7769/

- Återvinningsstudie av metallpulver för AM http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2014-00597/Atervinningsstudie-av-metallpulver-for-AM/
- Nytt nickelbaserat material för additiv tillverkning av komponenter för högtemperatur-applikationer http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2013-02373/Nytt-nickelbaserat-material-for-additiv-tillverkning-av-komponenter-for-hogtemperaturapplikationer/
- Digitalisering av komplett produktionsflöde - en förutsättning för additiv tillverkning (DINA) http://www.vinnova.se/sv/Var-verksamhet/Innovationssatsningar/Digitalisering-av-svensk-industri/Sma-puffar/Digitaliserat-produktionsflode/
- Färdplan för forskning och innovation för industrialisering av additiv tillverkning av metaller i Sverige (RAMP-UP)

http://www.metalliskamaterial.se/sv/forskning/fardplan-for-industrialisering-av-additiv-tillverkning-av-metaller/

- Flexibel tillverkning av funktionella kopparbaserade produkter
  http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2014-00600/Flexibel-tillverkning-av-funktionella-kopparbaserade-produkter/
- Additivt tillverkade verktygsdelar för flexibel produktion och optimerade produktegenskaper (AMtoFlexs).
  http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2014-00600/Additivt-tillverkade-verktygsdelar-for-flexibel-produktion-och-optimerade-produktegenskaper/
- Snabbare introduktion av additiv tillverkning genom digitaliserad kvalitetssäkring och digitala produktlager
  http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2014-01141/Snabbare-introduktion-av-additiv-tillverkning-genom-digitaliserad-kvalitetssakring-och-digitala-produktlager/
- Verifierad digital optimeringsarena för verktygsproduktion genom 3D-metallprintning
  http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2014-01141/Verifierad-digital-optimeringsarena-for-verktygsproduktion-genom-3D-metallprintning/
- Framtida direkttillverkade metallstrukturer (DirektMetall)
  http://www.vinnova.se/sv/Ansoka-och-rapportera/Utlysningar/Effekta/SIP-metalliska-material--barande-ideer-for-starkt-konkurrenskraft--genomforbarhetsstudier/
- 3D Print
  http://www.vgregion.se/upload/Regionutveckling/EU/SFP/Projektkatalog%20strukturfondsprogrammen%202014-2020.pdf
- 3D PrintPlus
- Hy-Las

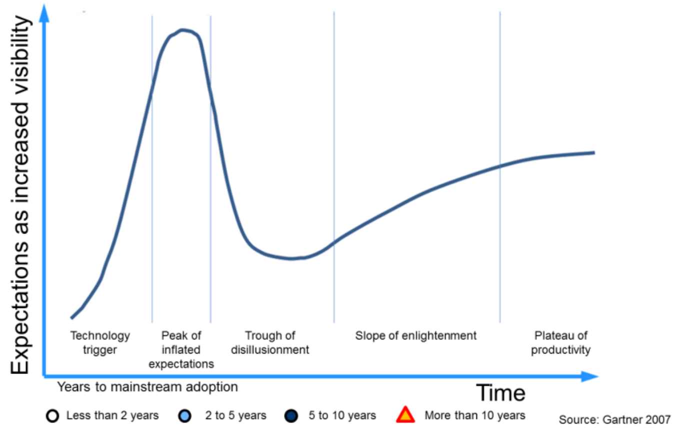
https://www.hv.se/forskning/forskningsprojekt/teknik/hybrid-sensing-for-understanding-of-laser-welding-technology-for-process-control-hy-las/

2017:

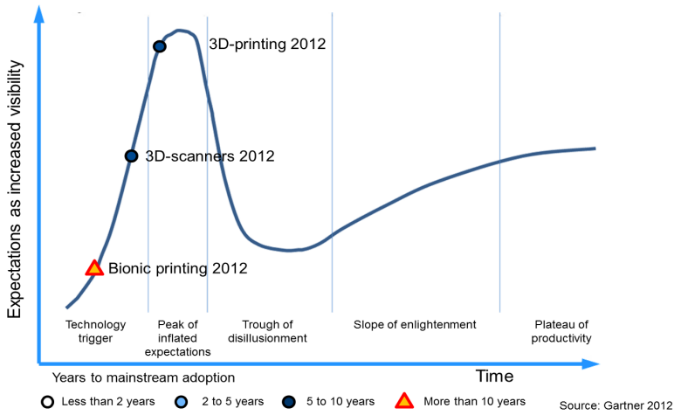
- ReLed-3D Resurseffektiv och flexibel produktion inom fordonsindustrin genom additiv tillverkning i metall
  http://beta.vinnova.se/p/reled-3d-resurseffektiv-och-flexibel-produktion-inom-fordonsindustrin-genom-additiv-tillverkning-i-metall/
- SUMAN-Next
  https://www.hv.se/en/research/research-projects/production-technology/suman-next/
- Synergi-LMDw
- Kompetenscentrum CAM 2
  https://www.chalmers.se/sv/institutioner/mmt/nyheter/Sidor/Miljonsatsning,-Nytt-centrum-f%C3%B6r-additiv-tillverkning.aspx
- Hälso-och miljöpåverkan av additiv tillverkning och dess utmaningar för en hållbar produktion-HÄMAT
- DINA++

IX. Appendix 7

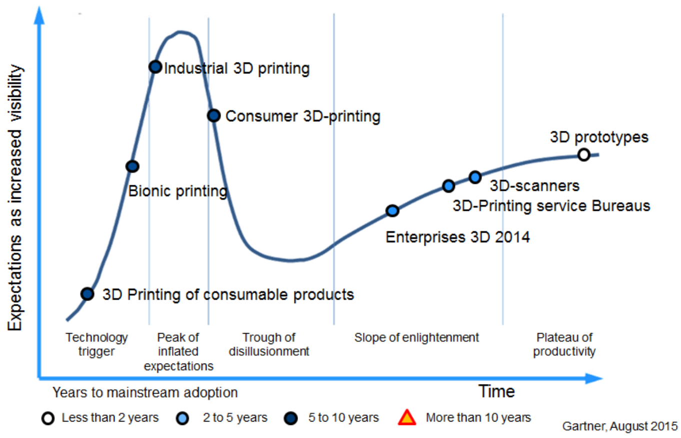
Gartner´s hype curves are shown in the following figures.



Gartner's Hype curve over 3D Printing July 2007, no 3D printing



Gartner's Hype curve over 3D printing July 2012 at the peak height. In 2012, 2013 and 2014 the interest peaked as massive media coverage.



Gartner's Hype curve over 3D printing August 2015

In 2016 the picture is the same as in 2007 (first figure) meaning no 3D printing at hype but with an interesting technique of 4D printing coming up at the technology trigger point.

X. Appendix 8

Companies listed on stock markets

Hewlett-Packard (NYSE)

Hewlett-Packard is not strictly a 3D printing company. With a market cap of $25.16 billion, the company is making inroads into the 3D printing market with its Multi Jet Fusion technology. As of January 16, 2017, shares of HP were trading at $14.77.

3D Systems (NYSE)

The company has a market cap of $1.86 billion and, as of January 16, 2017, its stocks are currently trading at $16.11.

Proto Labs (NYSE)

Proto Labs have a market cap of $1.42 billion. Stocks are currently trading at $53.55 per share.

Stratasys (NASDAQ)

Stratasys is headquartered in Minnesota and Israel; it has over 2,800 employees and holds 600 granted or pending additive manufacturing patents. The company has a market cap of $1.02 billion, and as of January 16, 2017, its share price traded at $19.37.

Materialise NV (NASDAQ)

Materialise is engaged in the field of additive manufacturing and only has a market cap of $407.97 million. As of January 16, 2017, its share price traded at $7.95.

ExOne (NASDAQ)

ExOne is another significant provider of 3D printing machines and related materials. ExOne has a market cap of $172.26 million. As of January 16, 2017, shares were trading at $10.55.

SLM Solutions (texDAX)

Listed in Frankfurt SLM has a turnover of € 80 million. On February 20th stock is traded for €39.

Renishaw (LON)

Like HP it is difficult to get information of the sales of their 3DP but they have a total of£436.6 million with a revenue of £80 million before taxes. The company with headquarter in Gloucestershire, UK has 4286 employees worldwide.

Arcam (STO)

Arcam shows in October 2016 a turnover at 616.2 million SEK for the last twelve months. The revenue was at the same time was -0.7 million SEK. Shortly after this announcement GE placed a bid for majority in Arcam.But some of the companies are not listed on the stock market like;

EOS

The company has grown with 30% every last five years. Has a turnover of €315 million with a staff 1000 employees. More than 3000 machines installed worldwide. Split between plastic and metal is roughly 60/40. EOS has increased its assembly capacity to deliver 2000 machines per year.

XI. Appendix 9

Published AM standards

Nomenclature and data formats

- SS-EN ISO/ASTM 52900:2017 ”Additive Manufacturing – General principles – Terminology”
- SS-EN ISO/ASTM 52921:2016 ”Standard terminology for Additive Manufacturing – Coordinate systems and test methodologies”
- ISO/ASTM 52915:2016 ”Standard Specification for Additive Manufacturing File Format (AMF) Version 1.2”
- SS-EN ISO 17296-2:2016 ”Additive Manufacturing – General principles – Part 2: Overview of process categories and feedstock”
- ISO 17296-4:2014 ”Additive Manufacturing – General principles – Part 4: Overview of data processing”
- VDI 3405 ”Additive Manufacturing processes, rapid prototyping – Basics, definitions, processes”.

Materials

- ASTM F2924-14 ”Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion”
- ASTM F3001-14 ”Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion”
- ASTM F3055-14a ”Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion”
- ASTM F30565-14e1 ”Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion”
- VDI 3405 Part 2.1:2015-07 ”Additive Manufacturing processes, rapid prototyping – Laser beam melting of metallic parts – Material data sheet aluminium alloy AlSi10Mg”

Testing

- SS-EN ISO/ASTM 52921:2016 ”Standard terminology for Additive Manufacturing – Coordinate systems and test methodologies”
- SS-EN ISO 17296-3:2016 ”Additive Manufacturing – General principles – Part 3: Main characteristics and corresponding test methods”
- ASTM F3049-14 ”Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes”
- ASTM F3122-14 ”Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes”
- ASTM F2971-13 ”Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing”
- VDI 3405 Part 2 ”Additive Manufacturing processes, rapid prototyping – Laser beam melting of metallic parts – Qualification, quality assurance and post processing”

XII. Appendix 10

Examples of powders available for AM manufacturing according to powder manufacturers

Stainless	Fe-base and Tool steel	Titanium	Aluminium	Hard metals	Nickel-based	Cobalt-based	Precious
304L S30403 1.4307	H13 T20813 1.2344	Pure Titanium	AlSi12		625 N06625 2.4856	CoCr F75 R31537	Gold
316L S31603 1.4404	X40Cr14 - 1.2083	Ti6Al4V	AlSi25		718 N07718 2.4668		Silver
420 S42000 1.4034	4140 G41400 1.7225	Ti5Al2.5Sn	AlMg3		738		99,9% Cu
? J94224 1.4848	M300 (K93120) 1.2709	Ti6Al2.5Sn 4Zr2Mo	AlSi10Mg		939		CuSn
15-5PH S15500 1.4545	INVAR 36 K93601 1.3912	Ti5Al5Mo 5V3Cr	AlSi7Mg		230 N06230 2.4733		
17-4PH S17400 1.4542		Ti6Al7Nb	AlSi9Cu3		Waspaloy N07001 2.4654		
347 S34700 1.4550			AlMg4.5Mn0.4		HX N06002 2.4665		
Duplex 2205 S32205 1.4462					C-276 (N10276?) (Ni 6276?)		
2507 *S32750* *1.4410*					(C-1023?)		