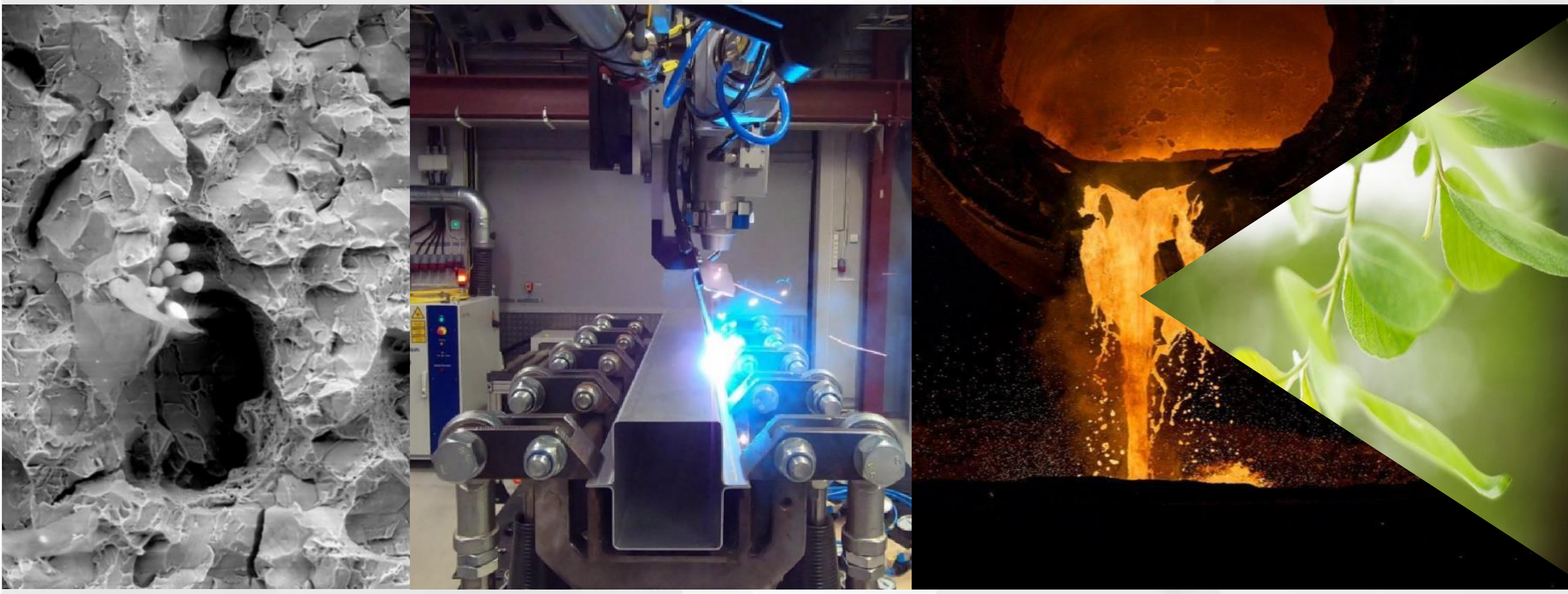

FuRAM – Follow-up on research needs for industrialization of metal additive manufacturing

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Abstract

Metal additive manufacturing (AM) has great potential for certain applications and many good examples have been shown. Some products are already in production, globally as well as in Sweden, and the market forecasts show exponential growth the coming years. In 2016-2017, a roadmap called RAMP-UP - *Roadmap for research and innovation to industrialize AM of metals in Sweden* was made [1], followed by a SIP Metallic Materials AM-call based on the conclusions [2]. This project, aims to summarize the state-of-the art of metal AM, evaluate the current status of the roadmap, and the effect of the funding. Furthermore, the updated most prioritized needs from industry in Sweden has been collected.

The forecasts for the metal AM market are still optimistic, even if a dip occurred in 2020. Compared to 2019, the size of the metal AM market is expected to double until 2025 and be five times the size in 2030. Significant steps have been taken the last years in several areas and many great examples of industrialization can be seen. In Sweden, some companies have products like powder, equipment, and AM components in production on high TRL-levels. However, widespread industrialization is taking longer time than expected.

Funding of metal AM research in Sweden from different agencies sums up to almost 600 MSEK for 2010-2020. Only in 2020, the funding was 160 MSEK. Additionally, in-kind contributions from industry and other stakeholders are on approximately the same level. All RAMP-UP areas, that were identified in 2017, have been explored to different extent during the last years. Progress has been made regarding many of the RAMP-UP challenges, but more efforts are needed in all areas. The effect of the funding is expected to speed up the industrialization of metal AM in Sweden. In some soon to be finished SIP Metallic Material projects all companies answering a survey (6 of 9) plan to release new products within 0-5 years, supported by the project results.

According to the Swedish industry, these are the current areas of highest priority for national support:

- AM eco system development
- Quality assurance
- Industrialization efforts
- Powder, material, and process development
- Environment, health, and safety

Getting from a technology push to a market pull situation, building trust for the technology and among stakeholders along the value chain, is key to growth and prosperity.

Table of contents

Introduction

Metal additive manufacturing (AM) has great potential for certain applications and many good examples have been shown. Some products are already in production, globally as well as in Sweden, and the market forecasts show exponential growth the coming years. In 2016-2017, a roadmap called RAMP-UP - *Roadmap for research and innovation to industrialize AM of metals in Sweden* was made [1], followed by a SIP Metallic Materials AM-call based on the conclusions [2]. This project, aims to summarize the state-of-the art of metal AM, evaluate the current status of the roadmap, and the effect of the funding. Furthermore, the updated most prioritized needs from industry in Sweden have been collected. The project group carrying out the work in both RAMP-UP and FuRAM essentially consists of the business management group of "The Swedish Arena for AM of Metals" [3].

1 State of the art

The status of metal AM has been summarized in this chapter focusing on market expectations, major events and challenges in the world influencing AM, status of industrialization, status of research, and significant steps during the last years.

1.1 Status of industrialization

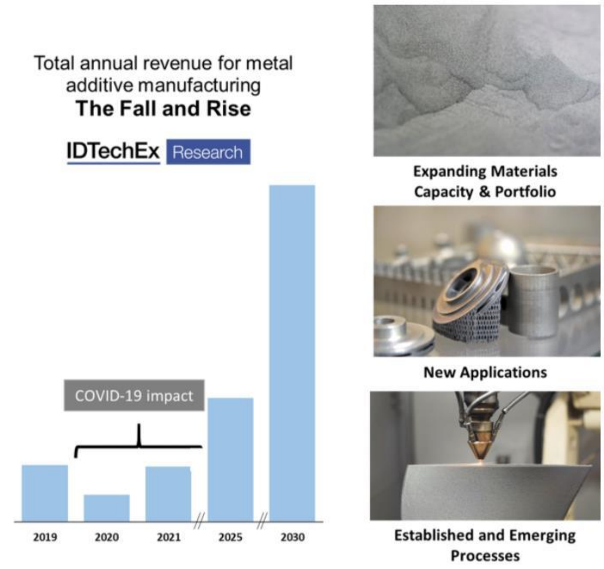
In this section the status of industrialization world-wide and in Sweden are summarized and compared to the market expectations.

1.1.1 Market expectations

The forecasts for AM industry are still confident; 3,5 times growth by 2026 compared to 12,8 billion USD in 2020 [4] is expected and there are similar high expectations by others [5] [6].

The metal AM market is valued at EUR 2.03 billion in 2020 with an expected Compound Annual Growth Rate (CAGR) of 29.2 % until 2025 [7]. There was a fall in metal AM market in 2020 but compared to 2019 the size of the market is expected to double until 2025 and be five times the size in 2030 according to IDTechEx in Figure 1 [8]. While the market predictions of 2017, which often forecast 50 or 100% growth in the coming four or five years, have been replaced by projections of 10-30 %. These predictions are still highly positive in the context of a global manufacturing industry which is preparing for a challenging future [9].

The technology that dominates the market for metal AM is powder bed fusion (PBF). There has been a decrease in sold metal PBF machines the last years, which has been a challenge for many suppliers, but the expectations for the future in Figure 2 are still optimistic [4] [7].



The fall and rise of the metal additive manufacturing market. Metal Additive Manufacturing 2020-2030

Figure 1 Metal AM Market 2020-2030 according to IDTechEx [8]

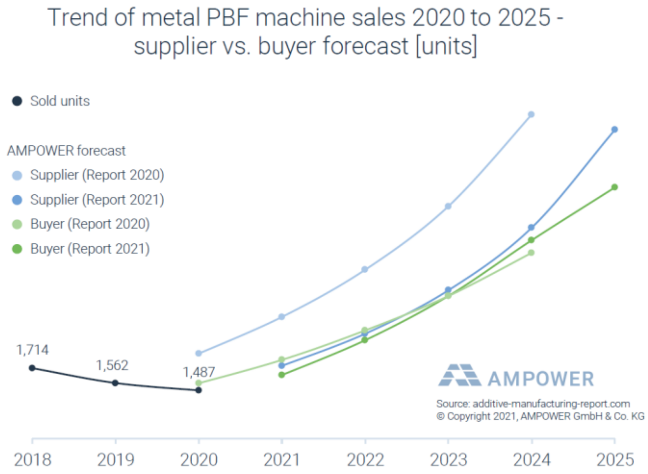


Figure 2 Metal PBF machines sales 2020-2025 [7]

1.1.2 Major events and challenges in the world influencing AM

The Covid-19 pandemic has had a negative impact also on the AM market, when maintaining existing production has been prioritized over the development of new technology and products. The pandemic has set focus on questions around self-sufficiency and local production, where AM could be an enabler. Additionally, this could lead to reduced transports with a positive effect on sustainability. A sustainable industry in general is a must, where AM can play an important role. Today’s transformative society, with respect to industrial development, is governed by three important developments:

- The electrification of society and transports
- The digitalization of society and information handling
- The development of more sustainable society with sustainable industry

Overall, these developments have and will have significant impact on the development and applications of metal AM as well. Electrification will require different drive-line architecture with new types of components with different material properties, as they experience different load history during their lifetime [10]. Unique solutions and materials for energy storage applications (e.g., fuel cells, and batteries) can also be developed by AM [11] [12]. As AM is a novel technology, based on a digital file, it is well suited to develop digitalization solutions from the start. Subsequently, those solutions can be transferred to other areas. For sustainability, AM can contribute in many ways like better material utilization, local production, produce on demand, etc.

1.1.3 Industrialization

Examples of industrialization of metal AM are found in a number of applications in different branches, see Figure 3, but so far wide industrialization is not there yet. This is noted by the powder producers, who have made investments into capacities both in Sweden and elsewhere but are still waiting for the powder volumes for AM to reach the published market forecasts. One indicator of the degree of industrialization and the maturity of a technology is the system utilization. According to AM Power, only a few industries have adopted metal AM for a wide range of products and achieved near full-time production [13]. Researchers at MIT suggest that the implementation of AM remains constrained by the technology's maturity and the skills of the corresponding workforce. They also suggest that the fundamental economics of AM, at present, generally constrain its use cases – especially in volume – to those where the manufacturer can afford a cost premium for AM [14].

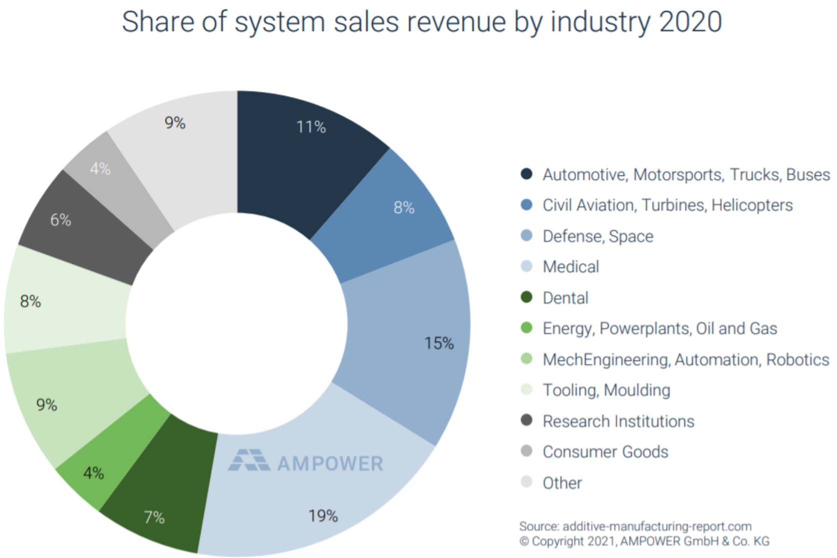


Figure 3 Shares of system sales revenue by industry 2020 [7]

Below follows a summary of the status of industrialization for some main business sectors. The medical sector was one of the first areas for industrialization and is today well established in the use of metal AM for medical and dental implants [15]. Hundreds of thousands of patients have received metal AM hip implants, beneficial for osseointegration (the fusion of bone and implant) [14]. Industrial applications of metal AM are also orthoses, protheses, and medical instruments and equipment [16].

Aerospace industry was also one of the early adopters, but as certification times are long, few critical components are on the market [17] [18]. There are a number of components where lightweight is utilized connected to interior design and AM helps to assist production activities (through prototyping, tool production) [14]. In Europe, one example of advanced application of metal AM in aerospace is the GE Avio Aero plant where EBM is used for manufacturing TiAl-blades, claimed to be made in volume production [19]. Products for space applications, e.g., products for satellites and rockets, are manufactured and both ESA and NASA have identified AM as a main technology area. Relativity Space are aiming to build rockets in 60 days using a large self-made DED-printer [20].

In the automotive sector, electromobility develops faster than expected and will change the manufacturing demand which might be an advantage for metal AM. Today, metal AM components can be found within racing and high-end vehicles. For aftermarket, small series, niche products, and prototypes, metal AM can be interesting for automotive in general [14]. For larger series, metal AM is not a feasible manufacturing method due to cost according to a panel discussion at Formnext 2020 [21]. However, the development of sinter-based AM technologies may constitute a game changer as these are potentially more fit for mass production than PBF and DED, but with other limitations, see Figure 6. Indirect AM, i.e., printing a mold in sand and cast complex parts, is also attractive for automotive. General Motors (GM) has announced the opening of an Additive Industrialization Center, a new 1,400 m^2 facility dedicated to AM for the automotive industry [22].

A break suspension link was the first AM safety-relevant part that has been approved (by TÜV SÜD Rail GmbH) for the railway sector in 2019 [23]. The work group “RAILability” consists of major European railway companies, SJ, DB, SNCF, Trenitalia and ÖBB and AM enterprises such as e.g. BeAM, ExOne, and EOS to cooperate in order to accelerate the implementation of AM in the rail industry [24] [25]. So far, metal AM is mainly being used for spare parts and reparations.

In the energy industry, Siemens Energy in Sweden is a good example of industrialization internationally, using metal AM for both manufacture and repair of components, see Figure 4 [26]. It is also explored within the oil and gas industry, even if the industrialization is progressing slower [27].

At Formnext 2020, the status and challenges for the general manufacturing industry were discussed as well and are well in-line with input from Swedish stakeholders given later in this report [28].

Figure 4 Production of more than 1000 gas turbine swirlers per year with qualified industrial production process at Siemens Energy [26]. *Picture curtesy Siemens Energy.*

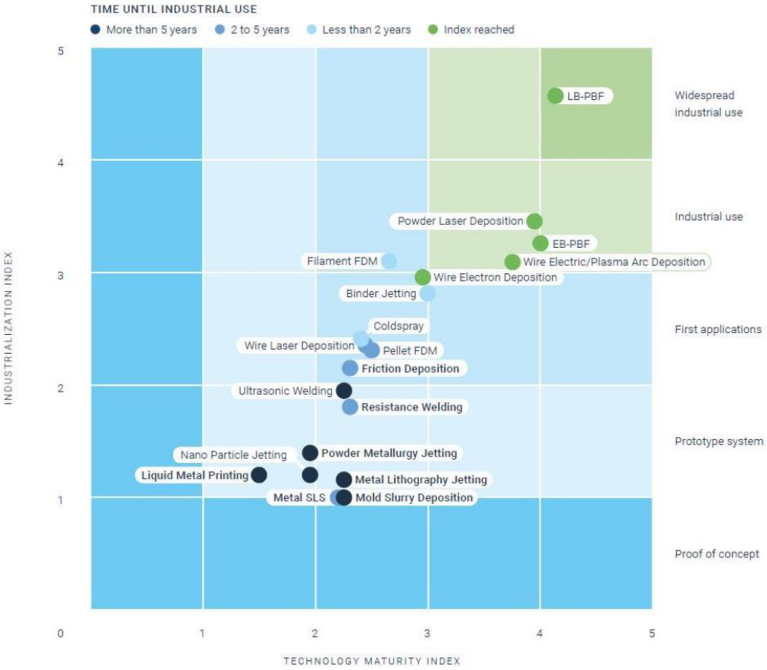


Figure 5 Technology maturity index plotted against Industrialization index [29]

Different AM technologies have also reached different level of maturity and industrialization, see Figure 5. In this plot, PBF-LB is seen as a metal AM solution that has reached maturity with regards to both technology and industrialization. Since 2017, AM solutions like PBF-LB, PBF-EB and powder laser deposition have matured, and we have seen more widespread adoption and industrialization. There are several new AM technologies that have not yet reached high index on either industrialization or technology maturity. However, they might come with higher productivity and lower system price that could support the market predictions for the coming years, see Figure 6. It is therefore important that there is continuous research in Sweden on new additive technologies that potentially could disrupt the ones we know of today and increase adoption even further. The most interesting ones around the corner is binder jetting (BJ) and different types of directed energy deposition technologies (DED), but the future disruptive AM technologies are probably not invented yet.

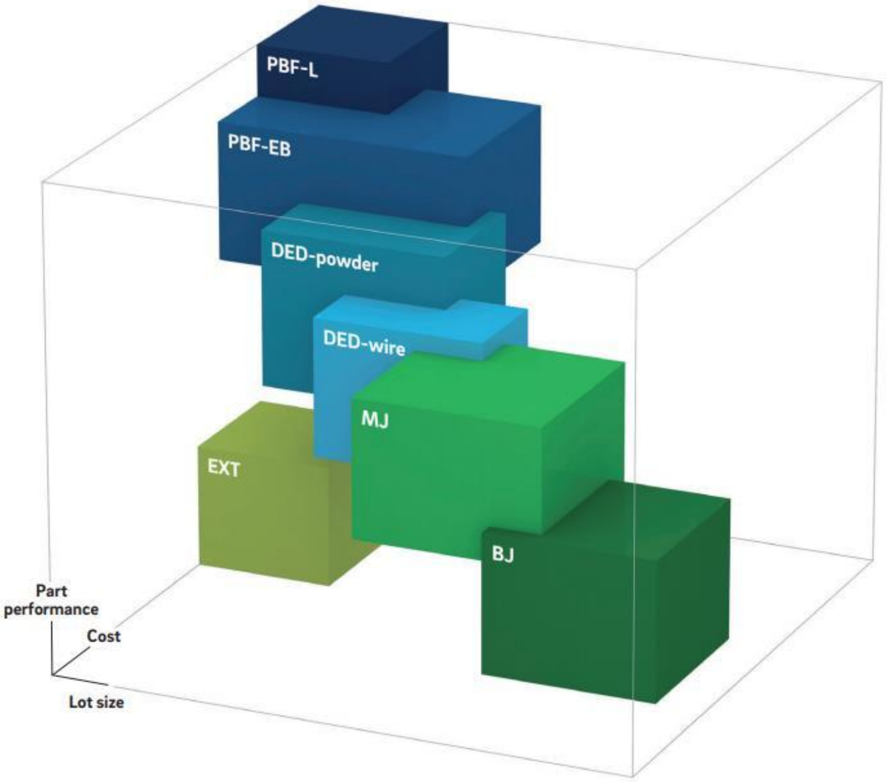


Figure 6 Comparison of part performance, cost and lot size for different metal AM processes [30]

1.1.4 Industrialization in Sweden

Traditionally, Sweden is a world leading supplier of metal powders where Höganäs, Sandvik, Erasteel, Uddeholm, and Carpenter Powder Products have commercialized powder for AM. New players are entering the market as powder producers, e.g., SSAB [31], Gränges [32], and Outokumpu [33]. Arcam (part of GE Additive), Digital Metal (part of Höganäs), and Permanova Lasersystem develop and sell AM-equipment for industrial production. In addition, Freemelt develops and sells AM-equipment for research, e.g., process- and material development. Quintus Technologies and Linde support the value chain with equipment for hot isostatic pressing and gas solutions, respectively. Components are manufactured in small series in Sweden, e.g., at Siemens Energy, Sandvik, GKN Aerospace (see Figure 7), Digital Metal, VBN Components, and Cytiva. Additionally, 3DMetPrint, Lasertech (now part of XANO

Group), AIM Sweden, and AMEXCI are also offering printing services for both prototypes and industrial components. Several end-users have components for different applications under development, using in-house or external printing resources, and some products are already industrialized. AM of novel materials like amorphous materials by Exmet Amorphous Technology are brought towards industrialization together with automotive industry in Sweden [34] [35]. A new small company is Procada, offering engineering services and customized process control solutions needed to achieve reliability, robustness, and repeatability in DED processes.

The activities around non-destructive quality control and inspection, for AM at the inspection service providers in Sweden, are still few. This possibly indicates that those that print today and require inspection, do this in-house with their own workforce, and/or do not print that much for production but rather for prototyping.

Figure 7 Pratt & Whitney aeroengine PW1500G/PW1900G with fan case mount ring manufactured by DED-LB/wire by GKN Aerospace [36]. Picture curtesy GKN Aerospace

A survey was sent to companies in Sweden with interest, activities and/or products within metal AM. The survey was spread through different channels; The Swedish Arena for AM of Metals, Vinnova competence center CAM2 and AM4Life, SIP Metallic Material conference, AMEXCI and personal contacts. 25 companies answered the survey, and they can be grouped according to Table 1.

Table 1 Companies answering the survey

Powder	Special material & process	Manufacturing	Equipment	Enduser	Support
7*	2	3	4**	8***	1

** 1 with own AM-production and applications*

*** 1 with own AM-production*

**** 3 with own AM-production*

One question was to estimate at what technology readiness level (TRL) [37] their companies are at regarding metal AM and to specify which products it refers to. The question allowed a company to answer for several products on different TRLs. The TRL refers to powder, component, equipment, material, AM-process, post treatment, and design tool. The product with the highest TRL-level for each company was plotted in Figure 8. All answers regarding TRL are shown in Figure 9. The companies also described their achievements in the last years in more detail clearly demonstrating that great progress has been made regarding implementation of metal AM and developing and releasing new products. The same estimation was not made in 2017 and hence, it is difficult to quantify the advancement and difference in TRL with time.

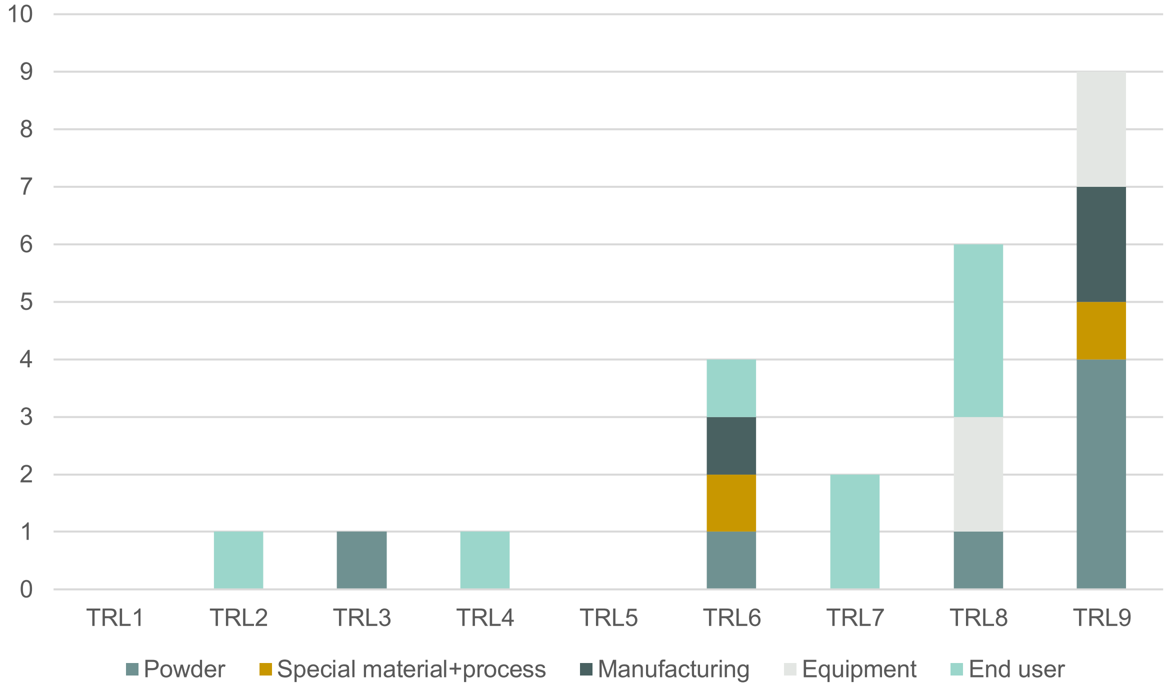


Figure 8 Product with highest TRL at each company answering the survey.

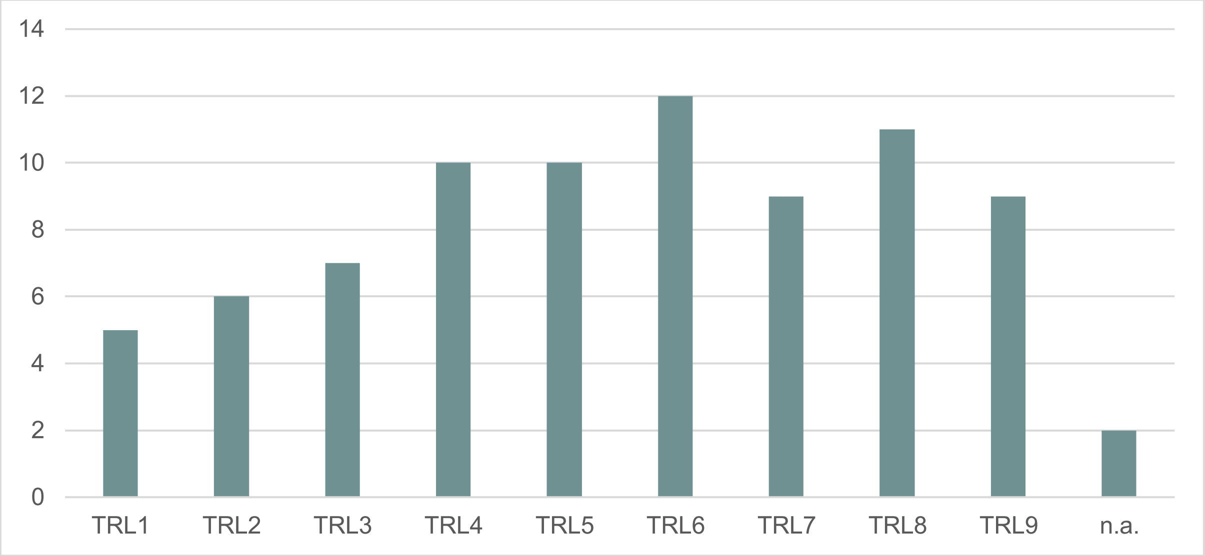


Figure 9 All answers regarding TRL from the survey. A company can have products on different TRL.

1.1.5 Discussion around GAP between market expectations and industrialization

For metal AM adoption, there is a gap between the high expectations from the market and the actual speed of industrialization. This is despite all significant steps taken for the technology the last years. Companies initiating metal AM production typically meet industrialization challenges with repeatability, part quality and productivity. Repeatability challenges in metal AM exists within one build, as part to part variation. It can also occur as build to build variation and machine to machine variation. For a part produced by one machine in a specific build, at a specific position, with a certain powder lot, to be same as another part produced by a different machine requires a robust system and a very good understanding of the critical process parameters. To achieve consistent part quality a quality management system is required with an establishes solid quality control plan with inspection intervals of the critical parameters. To decide on metal AM production, the parts coming out must not only meet the quality requirement. In order to be cost competitive compared to other methods, metal AM must also be productive. The productivity of a metal AM system is set by its design such as, number of lasers, build envelope size, recoating time and more. But system productivity is also depending on part design and the AM process parameters. If a part design is made lighter, less material is to be melted and productivity increases. The metal AM process parameters can be adjusted and optimized to productivity. But for all process parameters there is an operating window in which good part quality is achieved. There is always a trade-off between part quality and productivity, where good understanding of the overall manufacturing process is needed in order to reach balance and meet the need of all stakeholders. A company with series production of metal AM parts needs to control critical parameters and comply with both specific industry requirements and available AM standards. In recent years, several standards have been published that are available to enable adoption of the technology and allow suppliers and end-users to industrialize new AM applications faster, see section 1.3.7.

The market is expecting systems suppliers to increase productivity, robustness, build size and automation while lowering system price and maintaining good material properties, see Figure 10. AM metal powder suppliers are expected to lower price and widen their material portfolio.

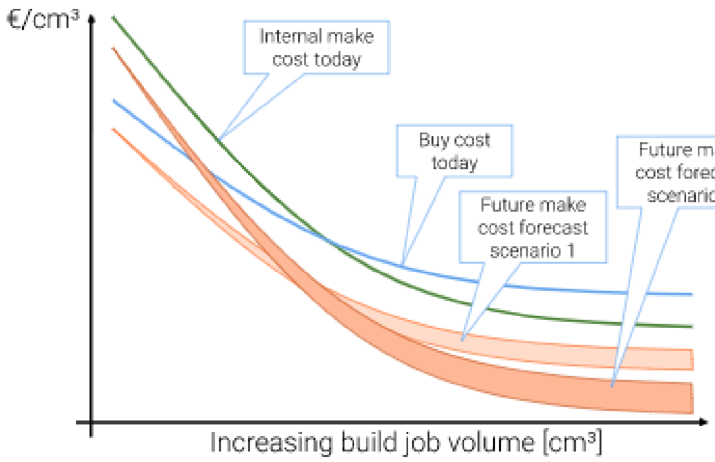


Figure 10 Cost of metal AM [38]

Strong drivers for selecting a manufacturing method are established supply chains and low cost of manufacturing. Manufacturers that consider metal AM and only look for replacing one method with another will often find metal AM to be more expensive only looking at the cost of manufacturing. To find the benefits of AM a company must be able to value other things, e.g. an increase of part performance, or see value in customization and a possible supply chain simplification, or the possibility to facilitate circular economy by using AM as a repair process, and so on. This makes part production a complex business strategy and the part life cycle cost must be considered [14]. How to model the part life cycle cost is a complex process and one of the main barriers in metal AM adoption.

If the AM market predictions are to be realized, a lot more companies have to find a way to assess the benefits and come to the conclusion that AM will offer a better overall total life cycle cost. Systems will likely become more productive and cheaper, and when adoption increases, powder price will decrease. To support this change, part life cycle cost models and guides specific for AM need to be developed to find the right business case and support the decision process for AM. Design for AM is an important key for the innovation process to create successful business AM cases. The design space for AM can be structured into three levels, i) Direct part replacement, ii) Adapt for AM, iii) Design for AM [39]. Design for AM includes, e.g., the ability to integrate functionality into one component, optimize use of material, reduce time needed in AM machines, and design to minimize support structures and post-processing.

A challenge in a Swedish context is to support the existing AM supply chain. This is not limited to powder manufacturing or printing capabilities but must also include post processing and quality assurance and control of additively manufactured or repaired parts. When an end-user designer considers not only manufacturing cost but also do the part life cycle assessment, AM will more often be the way forward. A designer must know that there is a strong supply chain and feel confident that AM path is feasible to not choose a proven established manufacturing method, despite potential upside with the AM path. Just as when there is a handover from a metal AM design engineer to the procurement department, there must be an established and healthy supply chain that understand the purchaser and can meet the industry requirements and complies to AM standards and certification.

Industrialization of AM is a journey a company does on its own and once done, it is not something you willingly share with others. There is a lot of time, money, complex decisions, and competence developed in this process. For the companies that can manage and afford this it is a strong factor of competitiveness. There is a need to develop guides and templates for work instructions, operating procedures, product and process validation and control plans for companies to know how to comply to standards and industry requirements, using AM.

1.2 Status of research and innovation

Status of research and innovation within metal AM, internationally and in Sweden, is described in this section.

1.2.1 Research internationally

It is difficult to find a comprehensive review of the status of international research in metal AM as it continuously expanding. What is clear though is that the level of research activities is maintained at a high-level, taking presence of AM as core topic on international conferences as well as its share with respect to other topics at such conferences. AM is a common core topic on international conferences [40] [41] [42] [43] [44] [45] as well as dedicated metal AM conferences [46] [47] [48]. For Euromat 2019, AM was the second largest topic after advanced steel with 118 and 127 accepted abstracts, respectively [40]. For Euromat 2021, AM is the largest topic and attracted the largest number of 102 accepted abstracts [49].

Scientific results in AM and hence research activities are continuously increasing. This refers not only to the increased volume of publications, see Figure 11, but also to overall impact and scientific level. AM journals attract high quality contributions with high impact factors, for example focus journals like Additive Manufacturing (Elsevier) has latest CiteScore factor of about 11.8 and Progress in Additive Manufacturing (Springer) has CiteScore factor of about 3.9 [50]. Further examples are high impact materials processing/materials design/material technology journals including articles on additive manufacturing such as Journal of Materials Processing Technology, Materials Design, Scripta Materalia, Applied Surface Science and Materials Science and Engineering. Overall, the CiteScore factor of Additive Manufacturing has increased from about 7.2 in 2017 to above quoted 11.8 in 2020, illustrating the overall significant development in the field. This is close to or overpassing the impact factors of classical journals in material science and metallurgy.

The topic of metal AM was taken up by several contributions in Nature Communications during recent years, including number of progresses across the whole field of AM with some highly cited examples of novel approaches in metal additive manufacturing [51] [52] [53] [54] [55] [56].

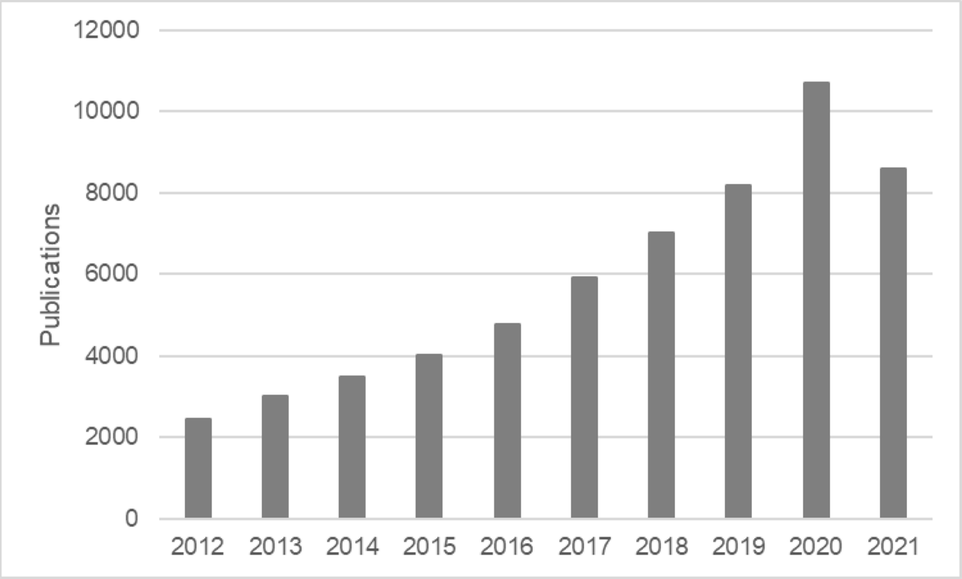


Figure 11 Results from searching for publications on Additive Manufacturing and Metal in ScienceDirect [57]. The number of publications is increasing every year and was all time high in 2020.

There are several active research centers in Europe, US, Asia and Australia. Many of them launched several years ago and are now progressing. To illustrate this, a few from different parts of the world are selected and some facts are summarized in Appendix 1. These few examples testify the active and significant R&D on the international scene and in many aspects the strong alignment with the activities in Sweden as identified via both the RAMP-UP and FuRAM projects. One important remark is that the research focus in international centres cover materials, hardware and process development, with many mostly focusing on material properties and performance assessment. Recent research trends focusing on AM integration across the value chain, development of technologies and knowledge in process monitoring, analytics and data treatment constitute new research direction for a number of the mentioned centres.

The centres presented in Appendix 1 have different size and differs significantly by the funding basis, many of which are supported through prioritized funding initiatives on national level, strong industrial funding and/or donations.

To this should be added number of company-hosted R&D centres. In Finland, EOS has its hub for materials and process development. To mention some important ones in Germany, the BMW Group Additive Manufacturing Campus, Munich/Oberschliessheim claimed to provide output >300,000 parts in metal and plastic [58]. There is also the Voestalpine AM-center in Düsseldorf with PBF-LB machines and areas of services [59]. Linde has its Linde Global Development Center for Additive Manufacturing in Munich with focus on technology development and customer support on powder for AM, AM process and post-processing development [60].

One way to measure innovation is the number of applications for patents. A search in the patent database Espacenet on the words *Additive Manufacturing* and *Metal* gave the diagram shown in Figure 12. In total, almost 1 million patents were published, and a peak can be seen in 2017.

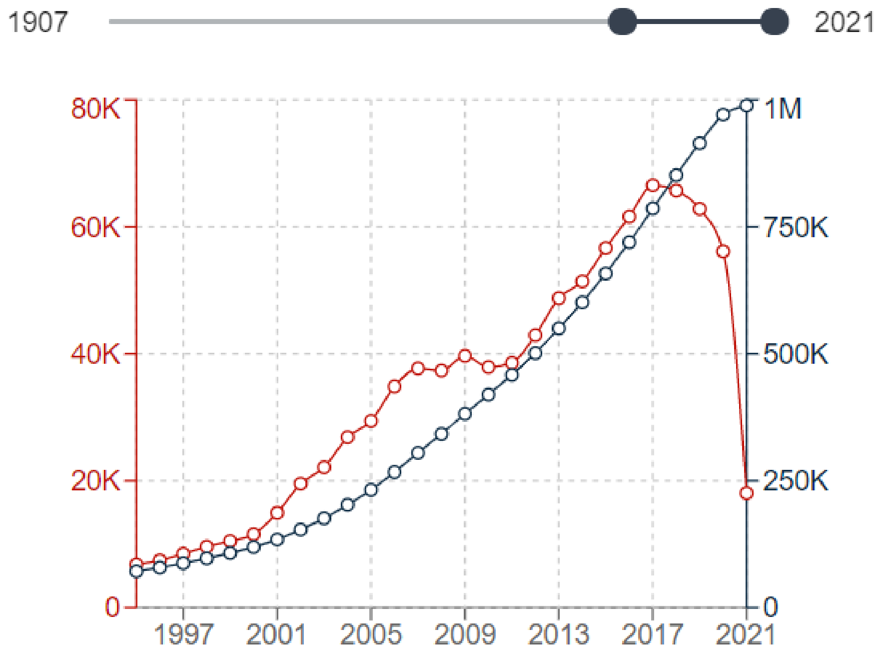


Figure 12 Result from Espacenet patent search on the words Additive Manufacturing and Metal [61]. The red curve shows patents per year and the black curve shows the accumulated number of patents.

1.2.2 Research in Sweden

Two Vinnova competence centers are now active; CAM2 (Competence Centre for AM-Metal, started 2017) [62] and AM4Life (AM for the Life Sciences, started 2020) [63], hosted by Chalmers University and Uppsala university, respectively. In addition, there is a strong established academic network in Sweden with more than dozen universities and research institutes actively involved in research in different aspects of metal AM, including Chalmers University of Technology, Dalarna University, Karlstad University, KTH, Linköping University, Luleå University of Technology, Lund University, Mid Sweden University, Jönköping University, Rise, Stockholm University, Swerim, University West, Uppsala University, Örebro University. Network with industry and academia interaction within metal AM are, e.g., The Swedish Arena for AM of Metals [3], TO80 at Jernkontoret [64], SIS TK563 [65], as well as many regional initiatives.

Most of the metal AM related research in Sweden is focused on material and AM process development and on advanced component characterization. A number of developments of AM-research has also been realized like new/improved materials (Ni, Al, steel), production speed increase (75% decrease of build time), new methods for assessing water content of powder, method for assessing argon content of powder, etc.

More than 50 PhD-students within metal AM started at different Swedish universities around year 2017 and many of them have now defended their dissertation or are just about to do so. New PhD-students are following, and the number of publications is increasing accordingly.

The number of AM-machines for research are increasing, the current number at universities and institutes accounts to at least 19 PBF machines (whereof 13 PBF-LB and 6 PBF-EB), as well as about 6 DED setups and one BJ in addition. Furthermore, a number of decisions for future investments are taken. Considering that the capacities cover different brands and different machine sizes, from smaller machines to real production machines, there is a comprehensive infrastructure on a national basis.

1.3 Significant steps the last years

Significant development can be seen in all areas the last years and are described below for manufacturing technologies, materials, post treatment, digitalization, automation, quality assurance and quality control, and standards. In most areas the development are based on incremental improvements rather than groundbreaking steps.

1.3.1 Manufacturing technologies

Metal AM has so far been based on number of core technologies, namely laser beam powder bed fusion (PBF-LB), electron beam powder bed fusion (PBF-EB), directed energy deposition (DED), and binder jetting (BJ). In addition, there is continued development of the AM technologies, e.g., development where metal powder is introduced into the polymer matrix filament used in material extrusion (fused deposition modelling) as shown by BASF based on their MIM compound [66], as well as introduced in the photopolymer bath used in the process VAT photopolymerization [67]. In both cases, final sintering is required as the material extrusion or VAT photopolymerization only represent the forming stage. Considering the whole field of sinter-based technologies including binder jetting, there is a lot of novel approaches along the line of two stage processes [68]. The main potential benefit with these technologies is that they are much more suited for mass production as they follow the logics of traditional powder metallurgy processing. Companies providing hardware and manufacturing solutions include Digital Metal, Exone, Markforged, Desktop Metal amongst others. However, the powder requirements are different as the same powder cannot be used for any sintered-based technology like binder jetting as for PBF-LB or PBF-EB.

In case of PBF-LB, the development focuses on increased productivity. New machines with multiple lasers (up to 12!) and advanced controls are introduced to the market, see e.g. [69] [70] [71]. Today, there are several examples of successful printing with layer thicknesses of 80-100 µm by using the same hardware compared to standard layers thicknesses of 20-40 µm some years ago. This alone constitutes an increased production rate of 2-4 times. In case of PBF-EB, novel hardware is launched from GE Additive (Arcam) and open-source solutions are provided by Freemelt, both companies based in Sweden. Recently, many new equipment suppliers of PBF-EB worldwide made a commercial entrance, including Jeol [72], Wayland [73], and others listed in Figure 13. Hardware solutions like LB_6 filaments are the standard choice rather than W filaments, which means significantly increased brightness and filament lifetime. Hence, the equipment manufacturers have continued to boost the technological capabilities in all powder bed technologies.

There is also a drive for DED development as it provides an important means of much higher production rate than the powder-bed technologies, as well as it is well suited for repair. The DED solutions can, e.g., be combined with flexible 5-axis solutions with capability of re-orienting the part to keep deposition control while building [75]. Considering DED, this solution also means that hybrid technologies are facilitated by equipment suppliers [76].

For mass production of small precision metallic parts, the development of material jetting constitutes a special development [77]. It is a technology in which nanoparticles are dispersed in liquid which jetted, with numerous of inkjet nozzles, onto a tray to fabricate numerous of parts in parallel, followed by support removal and final sintering. Continuing to the micro scale, electrochemical deposition is another process to keep an eye of for the future [78].

There is also significant progress in hybrid technologies such as 3D sand printing (3DSP), in which sand printing is used for creating a mold for metal casting [79] [80]. Alternatively, polymer printing has been applied to produce the ceramic mold which in turn was used for investment casting. The driving force for applying these indirect methods comes from the need to develop and fabricate more complex shapes and lightweight, which in turn also is a driving force given the direct fabrication via metal AM itself. Important benefits with e.g. 3DSP are large part size capacities, combined with light-weight design and potentially attractive cost breakdown. There are about 13 vendors for 3DSP equipment, with ExOne and Voxeljet being the leading ones [4].

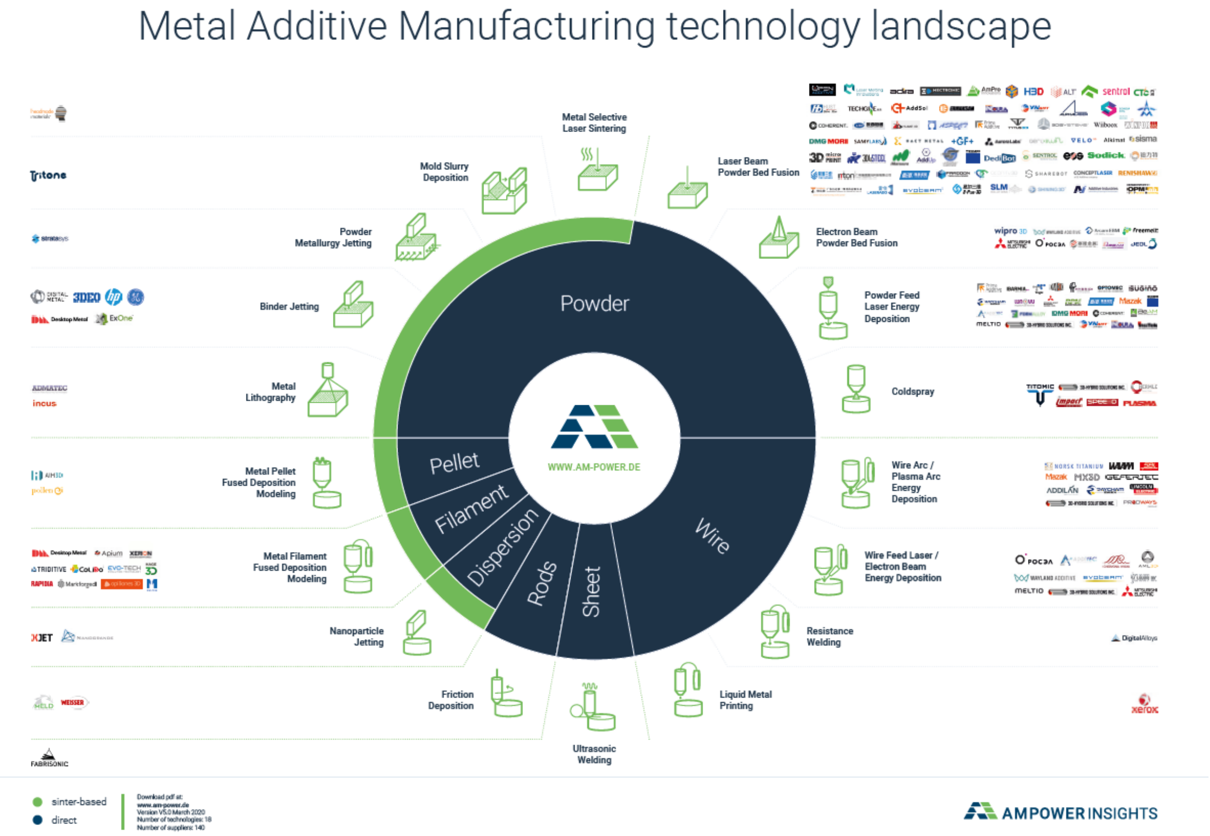


Figure 13 Metal AM technologies and suppliers [74]

1.3.2 Material

In recent years, the number of alloys commercially available as AM feedstock has increased notably compared to the 16 alloy systems (12 for PBF-LB and 4 for PBF-EB) available in 2017 [81]. The equipment suppliers provide around 30 alloy systems according to their webpages although it is not clear whether they all come with developed process parameter recipes for any part geometry or if modification will be needed from case to case. In addition, almost all metal powder producers already offer e.g. [82] [83] [84] [85] [86] [87] [88], or will offer e.g. [31] [89] [32] customized powders for AM to meet the customers' specific individual requirements.

In Table 2, alloy powders commercially available for AM are listed and the number of alloys is now >50. The alloys in Table X are not new AM alloys but were designed for thermo-mechanical processing histories typical for traditional manufacturing methods.

Table 2 Summary of common alloy systems currently availble for AM

Type	**Fe**	**Ni**	**Ti**	**Co**	**Al**	**Cu**	**Misc.**
Commercial	316L 4140LS 4340LS 420SS 431SS 347SS 347SS 17-4PH 15-5PH H13 Invar	C-276 Waspalloy IN 625 Hastallay-X Haynes 282 IN 718 IN 738 CM247LC René 80 Monel K-500	Ti6Al4V (different grades) Ti 4822 Ti 6242	CoCr CoCrMo CoCrW Haynes 188	AlSi10Mg AA2319 A205 F357 6061 4047	CuSn10 C-18150 Pure Cu GlidCop GRCCop42 GRCCop84	W Au Nb Ag Pt C-103 Ta
Research and development	Steel-MMC	Ni-MMC Single crystal alloys (René N5, CMSX-4)	B-Ti alloys Ti-Nb	SB-CoNi-10	Al-Cr-X Al-Mg-Sc (Scalmalloy) Al-MMC		High entropy alloys (multi-principal alloys)

The number of alloys designed specifically to take full advantage of the AM process conditions is still limited but some new alloy systems, specifically designed for AM are emerging, and have reached different TRL levels. For example, VBN Components has developed a new group of wear and heat resistant AM alloys (Vibenite®) for the PBF-EB process, and the company Exmet Amorphous Technology has expanded further through success of printing amorphous materials for various applications, e.g., electrical motors and electromagnetic components, using PBF-LB.

The availability of AM material feedstock for AM processes other than PBF-LB and PBF-EB has also increased since the 2017 RAMP-UP State-of-the art-report [81], in particular for the binder jetting process where, e.g., both Digital Metal and ExOne now offer several materials solutions. This includes several steels, Ni-base alloys and metal composites (steel/bronze or Tungsten/bronze) as well as pure Cu which is one of Digital Metals' latest materials release, see Figure 14 [90].

Figure 14 Bullhorn antenna made in pure copper by Digital Metal. Picture curtesy Digital Metal

Several alloying techniques to modify the powder to affect the microstructure evolution during printing of certain material systems have been demonstrated through academic research, see e.g. [91] [92] [93]. The industrialization of these alloying techniques and subsequent new materials will take some time although for, e.g., Al alloys, printable versions are already commercially available [94].

Integrated computational materials engineering (ICME) is now used also for material development for AM (see e.g., [95]). Intellegens.ai is offering machine learning for material and process development for AM based on knowledge from Cambridge University [96]. Oerlikon acquired Scoperta in 2017 and is offering a big data analytical software to design new materials including AM-materials [97]. Data handling is important for all predictions and NIST has built an AM materials database using the NIST Configurational Data Curation System [98]. The Swedish Arena for AM of Metals has started to collect data in research projects and for PhD-work based on the same system which is available to the Arena members. Find more about digitalization in section 1.3.4.

1.3.3 Post treatment

New technologies to improve the surface finish of AM-components have been developed [99], [100]. The processes are often combinations of chemical and mechanical surface finishing and polishing technologies and the exact procedure is the proprietary know-how of the company offering the technology. Some of the technologies also aim to clean channels from powder and remove support from inaccessible places, as well as improve the surface finish in channels and of complex features [101].

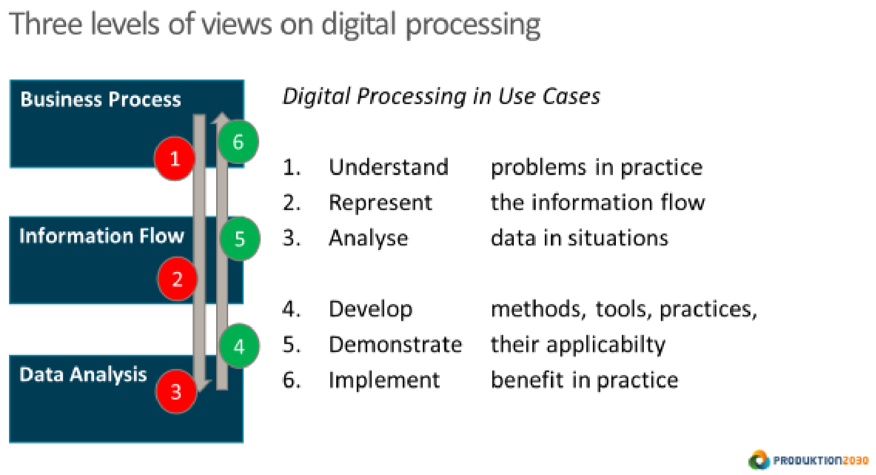
To design the support structures for easy removal is one way to reduce the need for time-consuming post treatment. New support free AM processes have been developed, e.g. by Velo3D [102], [103].

For critical applications, both hot isostatic pressing (HIP) cycles and heat treatments have been optimized specifically for AM materials [104] [105].

1.3.4 Digitalization

A technology roadmap for Digitalization in AM product creation chains, was presented in 2017 from the DINA pilot project ”Digitized production flow”, part of the Vinnova´s government mission to promote digitalization in Swedish Industry [106].

Since then, specific emphasis on digitalization and AM is made in three R&D testbed projects funded by SIP Produktion2030: DiLAM, DiSAM [107], and DiDAM. The digital processing from three levels will be described in an ongoing preparation of a “Digital Model Guide for AM” in Figure 15, based on several use cases in different materials made by different AM methods and combinations of them.



1. Understand problems in practice
2. Represent the information flow
3. Analyse data in situations

4. Develop methods, tools, practices,
5. Demonstrate their applicabilty
6. Implement benefit in practice

Figure 15 The three levels of views are applied in the AM use cases, to create a generic digital model guide for AM, ongoing work by Ola Isaksson, Chalmers, in P2030-project DiSAM.

The business process, illustrating the product creation flow in an overview AM product life cycle, is presented in Figure 16.

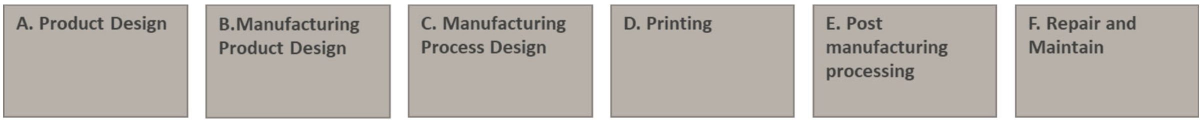


Figure 16 An overview of the business process steps, connected between each other by digitalization and material flow.

Digitalization within metal AM is developed by continuous improvements rather than groundbreaking steps during the last years. The RAMP-UP roadmap identified gaps in the digital flow between different steps, and such gaps can still be identified. Large actors in the AM market, have the ambition to cover a seamless flow through all steps and in all moments through the AM product creation steps. This means a continuous and intense work to refine, improve and integrate the digital information processing in all single steps. This, by using a combination of AM, big data handling, and artificial intelligence, e.g., machine learning. A specific quality improvement step in the digital information from design CAD to AM machines, is proposed, by replacing the current STL file format with a new AM file format. Examples of new formats are AMF (Additive Manufacturing File Format) and 3MF (3D Manufacturing Format) [39].

In parallel, there is a need to implement more basic functionalities, sensors etc in AM machines. To identify, understand and describe the digitalization that the future R&D needs, the digitalization stair in Figure 17 can be used as a tool.

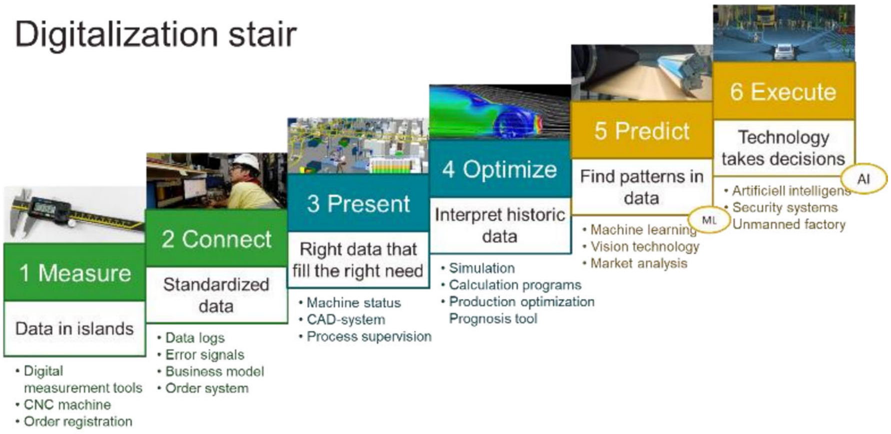


Figure 17 The digitalization stair, a model presenting how data can be used in different technology steps. Adapted from Industry 4.0 Maturity index by Sandra Mattsson, RISE.

The models in Figure 15 and Figure 17 can be used in the process of describing and understanding the current state of digitalization and the future needs from three perspectives:

1. The product creation steps from innovative ideas to realized components or products
2. The metal AM processes and machines: How to optimize AM for metal manufacturing.
3. The industrial metal AM production through the whole supply chain

Industrial digitalization needs a transparent, quality assured information flow in an enterprise functionality like ERP (Enterprise Resource Planning) – MES (Manufacturing Execution System) – SCADA (Supervisory Control And Data Acquisition) – PLC (Programmable Logic Controller) – I/O (Input/Output communication). In such “system of system”, new AM material properties, improved process and machine capabilities, also needs updated digital representation.

The connected society, factories and machines, are vulnerable for cyber-attacks, as well as misused information and misused intellectual properties (IP). An example of misused IP can be illegal AM of spare parts. The DiSAM project has introduced a specific use-case on IP and involved international software vendors to create a functional system in a supply chain. The data format used for the industrial design IP where STEP AP242. One of the addressed workflows had the following actors and simulated roles for the investigation; Epiroc – OEM, RISE IVF – AM Print house, Brogren Industries – Post process service provider & Swerim – Process simulation consultancy. The challenging part for protection of data is not the encryption of data, but how to unlock access in a controlled and convenient manner. The importance of the topic is illustrated e g by a new national innovation node for cyber security [108] and applications like VINNOVA´s “Cybersecurity for advanced industrial digitalization” [109].

1.3.5 Automation

Automated pilot systems from feedstock to produced product have been developed in e.g. the NextGenAM project (Premium AEROTEC, Daimler and EOS) [110] and the Hyprocell project (H2020) [111]. However, implementation of the systems is challenged by high investment cost. A full pilot line workflow optimization and automation using industrial robot technology and auto guided vehicles is established at RISE IVF within the MANUELA project (H2020), where Chalmers is the project coordinator [112]. Additive Industries released MetalFAB-600 in 2021, with more automation than their previous systems.

Systems for automation of parts of the process chain are on the market, but they are often not connected to other process steps. Loading and unloading of the build module, cut component from build plate, powder removal, and integrated chuck solutions for post processing are some examples. ExOne just introduced an automated guided vehicle to move the 700 kg heavy building box between the stations in their binder jet process.

If successful, automation would be beneficial for cost per part, work environment and repeatability. Still, the number of applications that needs automation today is small, but with development of automation more application will be feasible with AM [113].

1.3.6 Quality assurance and quality control

Quality assurance (QA) and quality control (QC) are broad but important areas for successful industrial implementation. The areas include process monitoring and process control, process stability, and non-destructive testing (NDT). Essentially, they deal with how to assure and control different aspects of quality, e.g., dimensional accuracy, surface conditions, mechanical properties, and material defect presence. The feedstock quality will also influence the performance of a component. It is possible to print, and to bring to market, high quality metal parts. However, QA and QC are still difficult, and to make high quality parts in a reproducible and cost-effective manner is still challenging [114]. In recent years, incremental improvements in quality assurance can be identified rather than single groundbreaking advances. An increasing amount of on-line process monitoring solutions is offered by the equipment providers and a number of international research developments are summarized below.

To correlate the measured powder properties to the processing in different AM technologies and to the final properties of a component is still a challenge, despite new guidelines [115]. Many methods to measure spreadability are under development [116].

The control of the build environment and the characteristics of the built part during the process is still an active research field. Within monitoring of the built part characteristics there has been a trend to add sensor and methods to detect imperfections and characterize also the sub-surface material; to complement the sensors for layer-by-layer surface conditions monitoring, already present in the commercial AM systems. The vision systems already implemented also include infrared and near infrared radiation detection, sensitive to both surface and surface close imperfections. One example of this for PBF-LB is the EOSTATE system for on-line monitoring that takes advantage of the laser-powder interaction to produce melt pool monitoring and optical tomography of layers as part is built [117]. Other AM system manufacturers have similar solutions. This technology allows to depict hot spots and number of event-based phenomena like, e.g., spatter formation responsible for potential defect formation. Still, the challenge is to connect the events to the physics of the process and to implement feedback loops with the aid if ML/AI routines [118].

Furthermore, additional sensors have been considered lately. Examples of such novel (for the AM application) sensor approaches recently explored are acoustic emission, where one listens to how the material state changes during the process, e.g., crack formation sounds, as for PBF-LB in [119]; and detection of backscattered electrons in PBF-EB setups [120]. Here, Friedrich-Alexander University in Erlangen has developed and implemented the so-called ELO (electron optical imaging), whereby layerwise feedback looping is possible to tune and accommodate the build parameter settings [121]. In 2016, Arcam released their add-on xQam, which is a novel built-in X-ray (rather than electron) detection system, currently utilized for auto-calibration of the system, but which could potentially be utilized also for material characterization.

Probably more important for the overarching goal of increased industrialization of AM, are the studies on how to transfer the data into reliable information about the actual build quality. This is still an active research question. For example, studies are exploring how to connect in-situ data to fatigue properties [122] and other mechanical properties [123], as well as possibly try to utilize it in qualification [124].

A recent advance within NDT for AM, especially with regard to industrialization, is the 2020 release of the ASTM guidelines for NDT of AM parts used in aerospace applications [125]. Even though it is essentially an overview of the NDT methods suitable, and a list of relevant AM (DED/PBF) material imperfections, and many questions are still open, it is an important milestone for the community. In addition, a similar guideline standard for NDT of AM parts is also being prepared in the joint ASTM/ISO working group and is probably going to be release in 2021. In general, several working groups are active within topics related to quality assurance and quality control and many new standards can be expected [126].

Among the different NDT methods X-ray computed tomography (XCT) is still dominating among the published studies. Apart from its predicted suitability for inspection of complex part geometries, the interest has been high also probably since it, with overall success, can be utilized for material characterization on small destructively cut-up samples. Studies on resonance testing has also shown progress during the last years. Both of these methods have been highlighted in the emerging standards and other reviews on NDT for AM. Although XCT is emphasized in this AM context it is important to remember that as with all X-ray absorption based imaging methods, it is a challenge to detect with confidence small contrasting material imperfections, with similar density as the base material, in large high density parts. However, one of the overall drives for implementing AM is the possibility to manufacture light weight parts, a drive which would then potentially on an overarching perspective counteract some of these fundamental XCT limitations.

Between process and in-situ monitoring and post-build inspection, where powerful inspection methods are envisioned to be included into the AM machines, lies the concept of in-process non-destructive evaluation (NDE). In connection to this concept, e.g., non-contact laser ultrasound has also seen an increase in interest for this application.

The issue with resource intensive NDT procedure derivation for the specific application at hand (all of them are highly dependent on what to detect (defects) and characterize and in what (part geometry and so on)) has been given little attention and no significant progress on this challenge has been reported.

1.3.7 Standards

The activity concerning development of standards is currently high and is following the AM standardization framework in Figure 18. It is developed and approved by ASTM F42/ISO TC261, who jointly are the major actors in this field. In spring 2020, a summary was made of published standards and those under development related to metal AM [127]. The need from Swedish industry was also collected. SIS TK563 participated in the work and will continue working to support the interests, based on active involvement from industry [65].

For continued updates of standards, published and under development, the following sites are recommended:

- ISO search link [128]
- ASTM F42, divided into different areas [129]

Many general AM standards are now existing and the work with specific standards regarding material, process, and applications is ongoing, generating new standards every year. From ASTM/ISO, two application specific standards have been published for aerospace and one is under development. For medical applications two standards are under development and for automotive and transportation and heavy equipment industries one each [129]. Besides the joint work from ASTM/ISO other standardization organizations are active. For example, application specific standards are also available from SAE; approximately 60 standards, published or under development, for aerospace [130]. Another example is the new DNV guideline for AM of metallic parts for oil and gas industry [131].

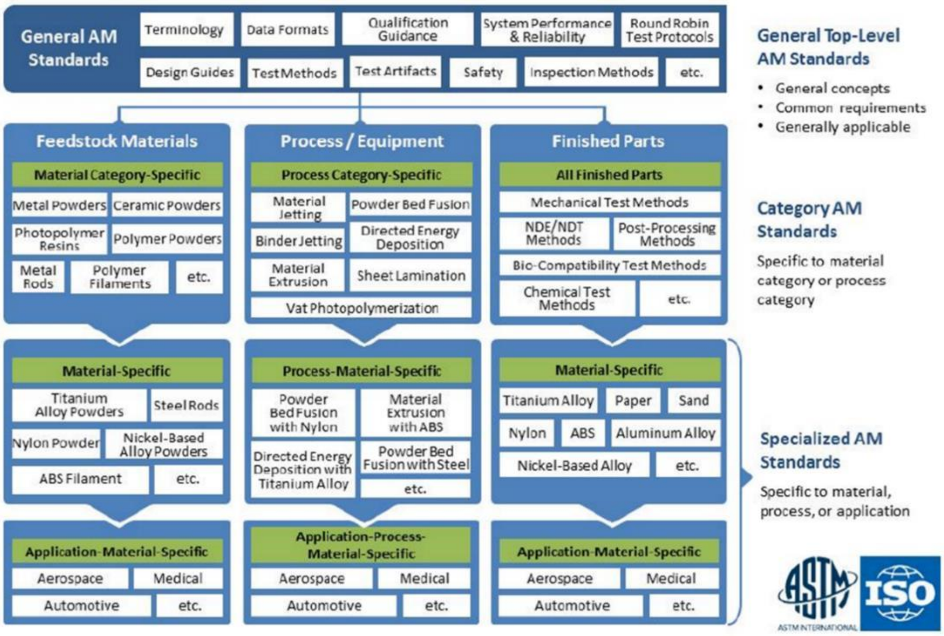


Figure 18 AM standardization framework, developed and approved by ASTM F42/ISO TC261 [132].

America Makes and the American National Standards Institute (ANSI) published their Standardization Roadmap for AM (Version 2.0) in June 2018. The roadmap described the AM standardization landscape and identified 93 “gaps” where no published standard or specification existed to address industrial needs. In 65 of the gaps, additional pre-standardization research and development needs were identified. The focus of the roadmap is the industrial market, especially for aerospace, defence, and medical applications. In 2021, a progress report was published that describes the progress to address the gaps identified and described in the roadmap [133]. The gaps progress report was compiled based on inputs from standard developing organizations, subject matter experts, alert mechanisms, and independent research. It lists newly published standards and new standards projects, alongside suggestions for future roadmap modifications. The report is not a consensus document but rather intended to serve as an interim “living document” that will be maintained and periodically re-published until that the next version of the standardization roadmap is available.

2 Roadmap status

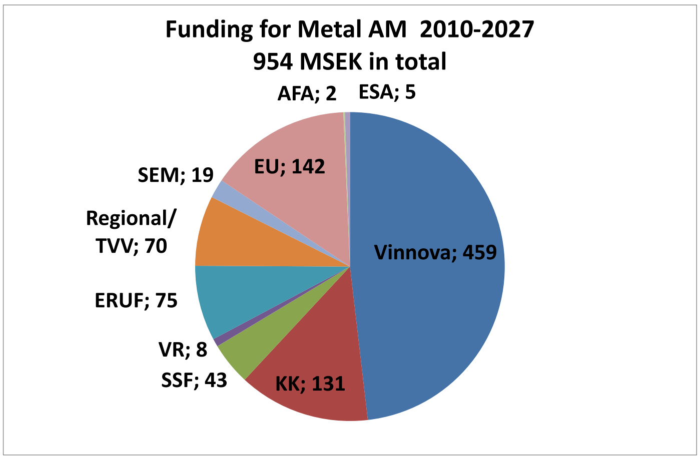
In 2016-2017, a roadmap called RAMP-UP - *Roadmap for research and innovation to industrialize AM of metals in Sweden* was made [1], followed by a SIP Metallic Materials AM-call based on the conclusions [2]. Part of the roadmap is enclosed in Appendix 2. A first attempt to evaluate the status of the roadmap is made here.

2.1 Research projects and their contribution to the roadmap RAMP-UP

National research activities contributing to the roadmap RAMP-UP have been collected and some effects described.

2.1.1 Research projects

Contributions to metal AM R & D projects including sand molds for metal casting granted in the period of 2010 – 2020 have been summarized in Figure 19 and Figure 20 by collecting information from 10 financiers. A few projects were also granted earlier and are not included in this study [134]. The funded period varies and today there are projects funded until 2027. The total contribution to Swedish academia and/or industry for the period is in the order of 955 MSEK and covers approximately 220 projects listed in Appendix 3. More information about the different projects can often be found in the SweCRIS database [135] and sometimes at the webpages of the funding agencies. Compared with the amount granted until 2018, the contribution for the 2 last years is almost 400 MSEK for 100 new projects. The value of the industrial partners in-kind contribution and/or partners own contributions are not included. There might be some missed projects. Probably, there has been metal AM activities as minor parts in, for example, Triple Steelix (from January 2021 Sustainable Steel Region) and the Vanguard initiative which are not covered. Vinnova is the largest financier followed by Knowledge Foundation (KK), EU-projects and Regional funded projects including ERUF. These five financing bodies cover more than 90% of the total volume. The contribution per year is based on information from the financiers. In case that detailed information was absent the total fund was evenly divided for the given project period.



KK – Knowledge Foundation

SSF – Swedish Foundation for Strategic Research

VR – Swedish Research Council

ERUF – EU Regional Funds

Regional/TVV – Swedish Agency for Economic and Regional Growth

SEM – Swedish Energy Agency

AFA – AFA Insurance

ESA – European Space Agency

Figure 19 Funding for Metal AM 2010-2027

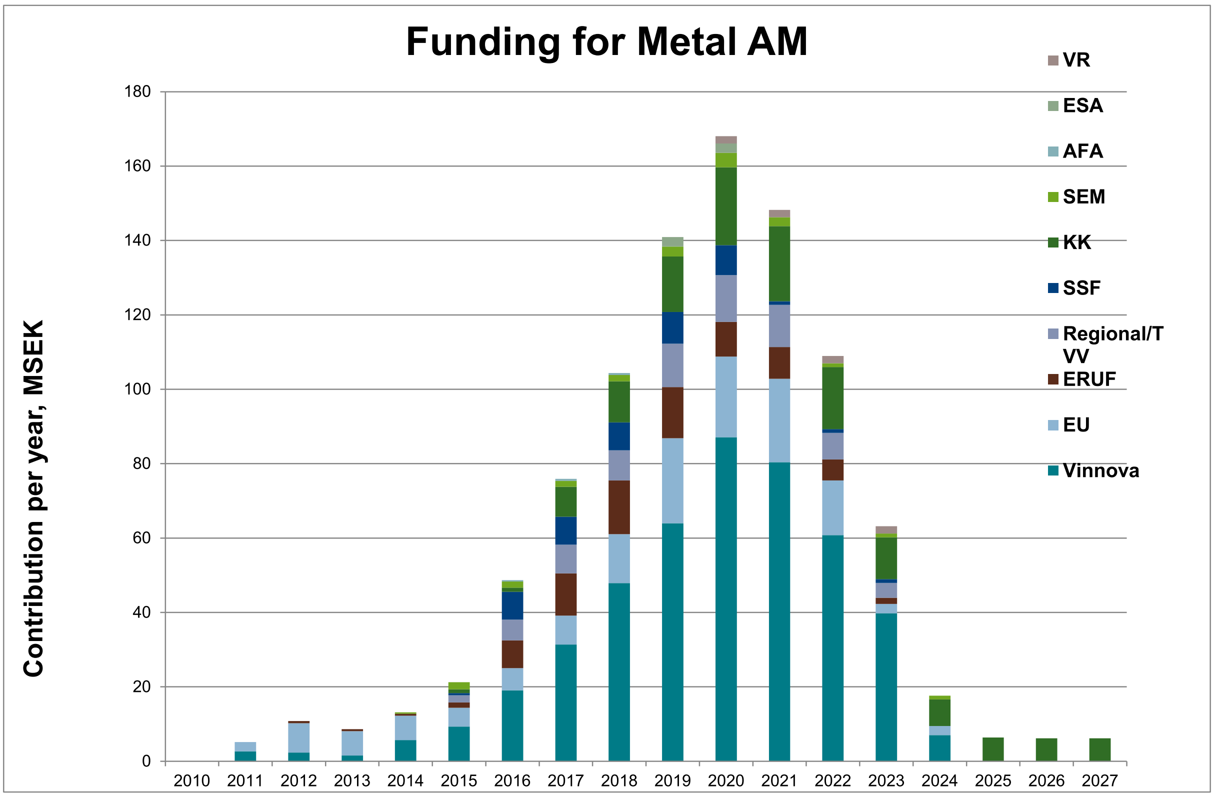


Figure 20 Funding for metal AM 2010-2027. Contribution per year for the project period.

2.1.2 Classification of the projects based on the RAMP-UP structure

The 220 funded projects have been classified based on the RAMP-UP structure in Figure 21. In addition to the seven RAMP-UP areas two new, Centra and Overall, were added. Projects classified as Overall usually contain pre-studies aiming at establishing national or regional test bed facilities and similar types of technical centra, where academia and industry work together.

Those projects are often funded by regional programs coordinated from the Swedish Agency for Economical and regional Growth. One project often relates to more than one area and the classification is based on the main challenge of the project, assessed by the FuRAM project group. Thus, the numbers should only be seen as rough approximations, and the volume of funding is also not reflected. Looking at the number of projects, almost half of the projects are within the areas "Production" and "Process stability and Product Quality". This is followed by "Material" and "Part and system design".

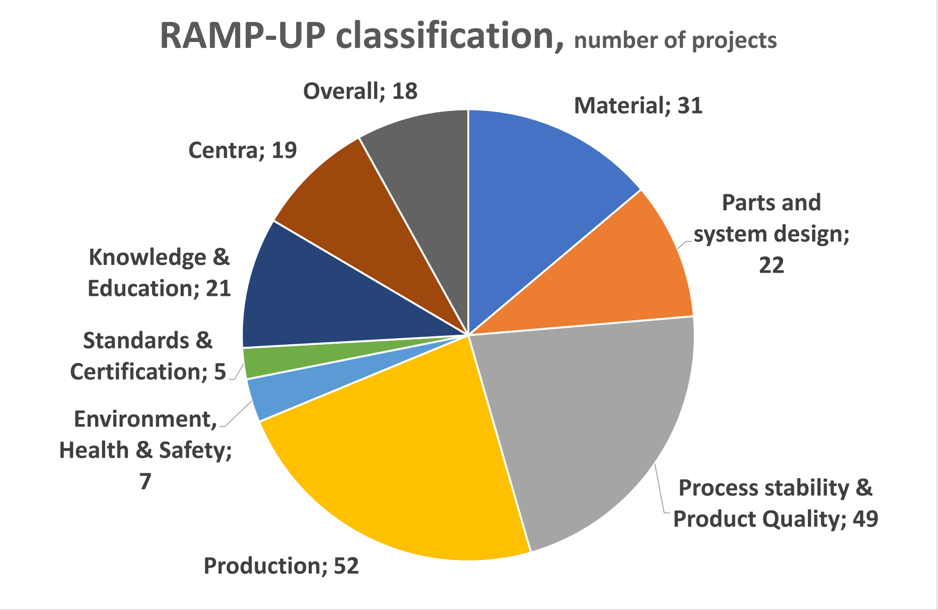


Figure 21 The projects grouped according to the RAMP-UP classification.

2.1.3 Effect of the projects from the SIP MM metal AM call

Nine projects were funded in the SIP Metallic Materials metal AM call 2018, based on the challenges with highest priorities from the RAMP-UP-project [2]. The industrial partners in all of these projects were asked about the effect of the projects and input was given from six of the projects (ADROAM, AMLIGHT, Amorph, DEMA, MiAMI, Sandbox). These projects mainly address challenges around material, process stability and product quality. All agree that the projects have contributed to progress around those challenges, but the challenges have not been entirely resolved yet. More knowledge and understanding have been achieved which both facilitates and motivates further development, as well as allows for prediction of key challenges.

Industrialization from all projects is expected within 0-5 years and the products are new powder materials, components, and input to software. The next step is verification and more evaluation in end-user applications. The development needs to be iterative based on the performance of AM-products in end-user applications. Increased productivity and lower cost would in some cases be needed to motivate the business cases. Post treatment for corrosion protection was mentioned as a missing process step to be developed for one product. One challenge for the last part of the industrialization is lack of internal time and resources, another is to involve additional partners to cover the whole value chain. Furthermore, technical challenges like simulation, process understanding, reproducibility and scaling are highlighted.

In general, it is a challenge to find applications with sufficient customer value to use AM. AM as a production method is still, for many applications, not mature with low productivity and high cost. Other challenges for industrialization of metal AM, mentioned by the project partners, are standards and knowledge. The complexity of product quality for an AM-component, e.g., microstructure dependance, was also mentioned.

Open general results and knowledge that will be available from the projects are good examples of AM development, methods for faster material characterization, methods for faster material and process development, possibilities for grain refinement, and process vs product quality knowledge. Based on the projects, new or better products will also be introduced on the market in the future.

Some of the project results are only for project partners, e.g., specific knowledge around development (alloy compositions, process conditions, post treatment) and around applications (demands, performance). The network and understanding of limitations and remaining challenges were also pointed out as important for the project partners. In the future, the effect of the projects for the project partners will be faster product development, improved products, competitiveness, and IP. For the sand molds, more efficient production is expected.

2.1.4 Reflection on knowledge

Looking at the Swedish project portfolio within metal AM the last years, some projects include many partners and have a broad scope to solve more generic questions around e.g., environment, health and safety (HÄMAT) and digitalization (DISAM). Those are areas where many companies need new knowledge and could collaborate without competition. Other projects are more focused on solving a challenge for a specific material, process, and application, and often include only a few different companies along the value chain. Dissemination of detailed knowledge from those projects is often trickier.

According to the project partners in the ongoing projects from the SIP Metallic Materials AM-call 2018, the projects will be able to cover both broad general as well as more narrow and deeper knowledge generation. The fact that all projects claim that the projects have contributed to industrialization of future products could be a sign of narrow and deeper knowledge directly applicable for a product. However, the willingness by the project partners to share broad general knowledge could be a way to contribute to marketing of future products or the company brand. It could also be a way to speed up industrialization of the whole metal AM business, which would increase the total AM market for everyone.

2.2 Status for the challenges and research questions in RAMP-UP

Progress has been made regarding many of the RAMP-UP challenges, but none of them has been solved completely. The RAMP-UP challenges identified in 2017 are still overall valid and of high priority. This conclusion can be drawn from the two surveys answered by industry, both the project survey (answered by 6 projects) and the general survey (answered by 25 companies). Many companies said that activities related to all RAMP-UP challenges within the seven areas were still important. Some companies highlighted specific challenges and those are shown in Appendix 4. The main areas in RAMP-UP are commented below.

Material: The number of available materials has increased as well as the methods for faster material characterization and development. Ongoing activities include better understanding of the existing materials as well as development of new materials.

Part and system design: In this area, innovation has just started. Some guidelines have been developed and more are under development. Improved design for AM could help to solve many challenges later in the process chain and could be one key to speed up industrialization.

Process stability and product quality: In 2017, a huge challenge was process stability, i.e., reproducibility and robustness. Components could be different from machine to machine, but also from position to position in the same machine, and from day to day. Since then, improvements have been made by both the equipment suppliers and the users and the focus have shifted to wider aspects of quality assurance and quality control.

Production: To scale up and industrialize metal AM, many production aspects need to be considered as can be seen by the high number of projects in this area the last years. Several activities around digitalization of the value chain are ongoing involving many partners.

Environment, health, and safety: A broad collaboration between experts and stakeholders has been established trough the project HÄMAT. Still, more work is needed to fully understand the potential risks and take appropriate measures.

Standardization and certification: Review of existing standards and needs from Swedish industry was collected in spring 2020 [127]. However, this is a continuous work in dialog with SIS TK563.

Education and knowledge: Education has been developed on different levels, for both industry and academia. Spreading of knowledge is still important.

2.3 Status of the short- and long-term vision

The following short-term vision was agreed on in RAMP-UP 2017:

> *For the next 5 years the overall vision is that a great number of small, medium and large sized companies have evaluated AM and thereby been able to set the direction for how to best utilize AM for strengthening their competitiveness, both nationally as well as internationally.*

To a large extent the vision has been fulfilled. Many companies have evaluated AM and some have products ready waiting for the increase of the market, that is forecasted. Other companies have evaluated AM but are struggling to find their business case. Still, many small and medium sized companies have not yet passed the first threshold of entering metal AM.

In addition, the following long-term vision was formalized in RAMP-UP 2017:

> *For the next 20 years the vision is that Sweden, by a fast and resource effective industrialization, has taken a pole position in key competence areas as well as a prime provider in a number of areas and applications.*

The status of the long-term vision is too early to evaluate but at this stage the vision could still be considered achievable. New players are entering the market and Sweden needs to be active to keep the pole position in key competence areas like powder metallurgy.

3 Research needs for industrialization of metal AM

Input from Swedish industry was collected through a survey, a digital workshop, and discussions. The input was grouped and analysed to be able to see overall trends.

3.1 Research needs and priorities

A survey was sent to companies in Sweden with interest, activities and/or products within metal AM. The survey was spread through different channels; The Swedish Arena for AM of Metals, Vinnova competence centers CAM2 and AM4Life, SIP Metallic Material conference, Jernkontorets TO80, AMEXCI, FOP (Swedish society for non-destructive testing), and personal contacts. 25 companies answered the survey. Below follow two questions related to needs and priorities and the answerers have been grouped and summarized.

Question: *What type of national actions would your company like to see to support the challenges you will address onwards?*

According to the answers the focus should be on:

- Real industrial applications
- Value chain development in collaboration
- Fundamental understanding
- Standards
- Education and seminars

To better understand the meaning of the first two areas some answers from the survey follow below. One specific idea was to focus on new technology of AM that could reduce the cost for production and another idea was to make a national 3D printing strategy to enable self-sustained manufacturing capability in crisis.

Real industrial applications

- Projects related to the use of AM in real industrial applications, such as spare parts, smart parts, tool parts, low volume production parts.
- More focus on actual applications and end-users of produced components. Application development.
- Aids that help the big OEM to see the advantages of using AM as production method.

Higher TRL – value chain development

- Calls directly focused on AM at higher TRL[1] spanning over several areas of the AM value chain to enhance industrialization – moving from prototypes to full scale production.

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[1] Comment: Though the required research activities could be at lower TRL

- We need to have projects where the entire supply chains are involved, from material producer to end-user and all the service providers in between.
- Supporting the Swedish AM service providers to grow, for example try to direct prototyping activities to AM companies.
- The focus should not be too pronounced on developing new materials or AM technologies but to rather industrialize those we have.
- Calls for AM initiatives where academia, SMEs and large companies cooperate to make sure that Sweden does not fall behind within AM in general as well as keeps its global position as one of the top AM powder producers in the world.
- AM ecosystem development on local, regional, national, international level.

Question: *If there was a new AM-call, would you join research projects (with in-kind)? In what areas? What do you think should be the highest priorities for such a call? What challenges would you prioritize?*

The areas with highest priority for a new AM-call at the moment are AM eco system development, quality assurance, industrialization efforts, material and process development, powder, and environment, health and safety. Below follow answers related to the different areas.

AM eco system development

- Projects with the entire value chain
- Closer connection to actual applications and product end-users (solving technical problems by AM, innovations made possible with AM, push the limit, design)
- Applications: Tooling, automotive, medical, general….

Quality assurance and control

- Quality control, product qualification, in-situ quality assurance, NDT
- Standardization

Industrialization efforts

- Increase production yield and process robustness
- Process monitoring, digitalization, simulation, AI or smart functions
- LEAN AM
- Automation (avoid manual handling)
- Gas applications
- Lower cost/better quality

- Upscaling, higher TRL
- Continuation of existing AM-projects (to take next step towards industrialization)
- Environment, health, and safety

Material and process development

- Process and material prediction and fundamental understanding
- Process parameters
- Material properties, fatigue properties
- Experimental verification of processes related to AM with simulation
- Post treatment, surface treatment
- Example pf materials: Tool steels, High strength aluminium alloys

Powder

- Powder production development
- Useful characterization as well as development of properties
- Understand the influence of powder characteristics on printability

A digital workshop was held on 7 May 2021 with 11 industrial representatives from powder manufacturers (4), equipment suppliers (3), and end-users (4). At least two of the companies have their own metal AM component production and others have access to internal or external printing. The workshop elaborated around the areas with highest priorities for a possible new metal AM call; AM eco system (value chain) development, quality assurance, and industrialization efforts (including environment, health, and safety). Powder, material, and process development was briefly discussed.

The workshop agreed that we are in a technology push situation, rather than a market pull. The only exception noticed was for some medical applications. To change this into a pull situation more trust would be required, both in the technology and among stakeholders along the value chain. Challenges are costs, high threshold to get started, complicated process chain (not just printing), qualification and verification, few standards, high secrecy due to competition, difficult to set/understand requirement, and lack of data and information.

Some solutions were proposed to build trust in the technology:

- Proof of concept – costs calculations, business cases, show benefits, inspiring applications,
- Lower threshold to get started – design for AM, testing without large investment, spread knowledge on all levels,
- Standards and guidelines around certification,
- Share data and information,
- Simulation of processes.

It was proposed that projects involving the entire value chain could potentially build trust for each other. It is also important to clarify different roles; who owns the challenge and how others can contribute to solve it. More input from end-users would be important to implement metal AM from different applications and focus on the challenges with highest priority. To build competence to be able to define and understand the requirements is a joint effort for the supplier and end-user. The requirements should be based on what is needed for the application and be adopted to the possibilities and restrictions with AM, and finally result in appropriate verification processes.

3.2 Possible areas where efforts would make a difference

Based on the given input from industry, the areas of highest priority are clear. However, to address the overall challenges, research is not the only solution. To change the situation from technology push to a market pull and decrease the gap between market expectations and industrialization, broader efforts are needed involving additional competences and building stronger collaborations.

It is important to involve the whole value chain to build a sustainable metal AM industry. One example is if national activities are initiated to lower the threshold for companies starting with AM, existing small AM component suppliers must be involved from the start. Getting more companies involved in AM will be beneficial for the suppliers in the long run, but can harm the short-term business, if subsidized testing is offered by other AM centers or universities.

Another effort is to assist in building an overall support structure with documents, guidelines, and tools covering quality assurance, business models, part lifecycle cost models, life cycle assessments, environment health and safety etc.

Finally, implementation and industrialization of the developments for research projects should not be forgotten.

3.3 Suggestions for wider knowledge spreading

Workshops and opportunities to meet and discuss experiences with others are often very inspiring and valuable. Since time is often lacking, recorded webinars could be a way to get knowledge whenever fitted into the calendar. Dissemination is an important part of all research projects and new ideas would be needed to reach an even wider audience. To include results from research projects into education, which is already done, is very effective. As the number of courses in metal AM are increasing in Sweden on all levels, more opportunities for this are given. A guide to existing education within metal AM in Sweden is planned to be made in 2021 within “The Swedish Arena for Additive Manufacturing of Metal” [www.AM-Arena.se]. Another way to increase and spread of knowledge could be publicly available summarizing written reports, short and long versions, of the final results from all projects. A guide to find interesting projects in different areas of interest would help here. Basic knowledge for people entering metal AM is sometimes harder to find, and a guide to available information and basic courses would also be valuable. We propose that existing platforms and networks should be utilized for these matters.

3.4 Updated version of the roadmap

The proposal from the project group is to keep the existing RAMP-UP roadmap as a base line. During time, the efforts will shift and need to be evaluated from time to time. The feed-back from industry is that the roadmap is still overall valid. Industrialization efforts are highlighted and can be found mainly within “Production”, but also in other areas. Quality assurance and quality control involves “Process stability and product quality”, but also “Material” and “Part and system design” and is supported by “Standards and certification”. However, many of the challenges addressed at present are not directly related to research and technology development, but rather overall national strategies. In this work more national stakeholders needs to be involved.

4 Conclusions

The forecasts for the metal AM market are still optimistic, even if a dip occurred in 2020. Compared to 2019, the size of the metal AM market is expected to double until 2025 and be five times the size in 2030. Significant steps have been taken the last years in several areas and many great examples of industrialization can be seen, but widespread industrialization takes longer time than expected. In Sweden, some companies have products like powder, equipment, and AM components in production on high TRL-levels.

Funding of metal AM research in Sweden from different agencies sums up to almost 600 MSEK for 2010-2020. Only in 2020, the funding was 160 MSEK. Additionally, in-kind contributions from industry and other stakeholders are on approximately the same level. All RAMP-UP areas, that were identified in 2017, have been explored to different extent during the last years. Progress has been made regarding many of the RAMP-UP challenges, but more efforts are needed in all areas. The effect of the funding is expected to speed up the industrialization of metal AM in Sweden. In a few soon to be finished SIP Metallic Material projects all companies answering a survey (6 of 9) plan to release new products within 0-5 years, supported by the project results.

According to the Swedish industry, these are the current areas of highest priority for national support:

- AM eco system development
- Quality assurance and control
- Industrialization efforts
- Powder, material, and process development
- Environment, health, and safety

Getting from a technology push to a market pull situation, building trust for the technology and among stakeholders along the value chain, is key to growth and prosperity.

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Some of the metal AM research centers

Centre	Location	Topics (in metals)	Infrastructure & materials (metal)	Funding	Notes
SC3DP https://www.ntu.edu.sg/sc3dp	NTU, Singapore	Aerospace& Defense (unmanned vehicles) Marine&Offshore Future of manufacturing	PBF-LB, PBF-EB, DED Stainless steel, tool steels, cobalt-chrome, nickel-base superalloys, titanium alloys,	National Research Fundation (NRF) NTU Economic Development Board Industry partners	
CAMAL https://www.camal.ncsu.edu	NCSU, Raleigh, NC, USA	Biomedical Aerospace& Automotive Hybride Manufacturing Logistics&Supply Chain Material Development	PBF-LB, PBF-EB, BJ Ti-alloys, Copper alloys, aluminium alloys, nickel-base superalloys, TiAl, Nitinol, niobium	Donations Industry partners	Mostly biomedical – infrastructure is donations with focus on implants for animals
NCAM (MTC) Including: ESA AM Benchmarking Centre ASTM AM Centre of Excellence https://ncam.the-mtc.org	Coventry, UK	Design for AM Materials AM Process Post-processing Simulations, Connectivity & Analytics	PBF-LB, BJ, FDM, DED	Catapult High Value Manufacturing Industry partners ESA ASTM Additional public funding	One out 7 Catapult centres in UK
MAPP https://mapp.ac.uk	Univ. Sheffield, UK[1]	Particulate Science and Innovation Integrated Process Monitoring, Modelling and Control Technologies Sustainable Future Manufacturing Technologies	PBF-LB, PBF-EB, DED Titanium alloys, aluminium alloys, nickel-base superalloys, high entropy alloys	Engineering Physics and Research Council Industry partners	EPRSC Future Manufacturing Hub

[1] Including research teams from Cambridge Univ., Leeds Univ., Manchester Univ., Oxford Univ. Imperial College

Centre	Location	Topics (in metals)	Infrastructure & materials (metal)	Funding	Notes
AMRC centre at The University of Sheffield: https://www.amrc.co.uk/	The University of Sheffield	Aerospace Designer Alloys for Selective Laser Melting - Optimization of Components for AM - Customised Oral and Maxillofcial Protheses using AM - Development of new materials for laser sintering - Process and Material development for High Speed Sintering - Manufacture of parts for end users including F1 teams using PBF-EB	PBF-LB and PBF-EB	Multipartnership centre Public funding Industry partners	
IAM http://iam.polito.it	Politecnico di Torino (Polito), Italy	Design for AM Process Simulation New Materials Process Chain Integration Big Data Sensors&Beams Systems	PBF-LB, PBF-EB, DED, gas atomizer, HIP Titanium alloys, nickel-base superalloys, TiAl, aluminium alloys, tool steels	Competence Centre since 2018 Public funding Industry partners	Links to GE Avio Aero/Polito joint lab TAL
ADME https://3dppan.eu/facility-centre/addme-lab-polimi	Politecnico di Milano (Polimo), Italy	Design for AM New Materials Powder Properties Digitalization& Monitoring& Big Data (AI, ML, etc) Multimaterials Performance (static, fatigue)	PBF-LB, PBF-EB, DED, BJ[2]	Department of Excellence status with public funding Industry partners	

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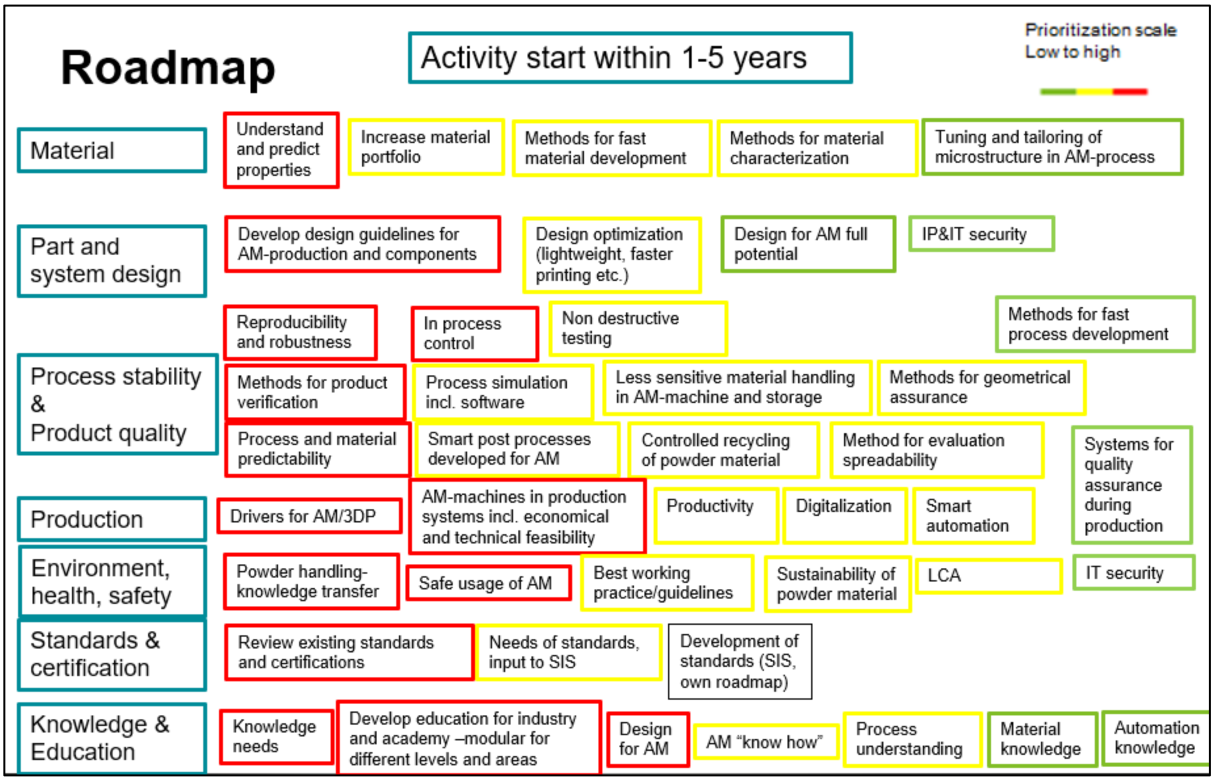
[2] Both Exone and Desktop Metal.

Centre	Location	Topics (in metals)	Infrastructure & materials (metal)	Funding	Notes
ACAM https://acam.rwth-campus.com	RWTH Aachen, Germany[3]	Design for AM AM processing Heat Treatment Post Processing Quality Assurance	PBF-LB, DED, EBM various alloys, graded structures	Multipartnership centre Public funding Industry partners	
ZMP https://www.zmp.fau.de/forschung/electron-beam-based-additive-manufacturing/ Application Centre VERTEC https://www.zmp.fau.de/forschung/vertec/	Friedrich-Alexander Universität Erlangen-Nürnberg (FAU), Germany	Alloy development Cellular Mechanical Metamaterials Process Strategies PBF-EB of Special Alloys Expansion Capability of SBEM by Improved EB Technology	PBF-EB, DED (LMD, LBM), Titanium alloys, TiAl, copper alloys, nickel-base alloys, cobolt-chrome	Public funding Industry partners Application centre	
DMRC Centre (Direct Manufacturing Research Center at University of Paderborn) - https://dmrc.uni-paderborn.de/	University of Paderborn, Germany	Material science and development Process development Mechanical behavior Design technology Costs Strategic investigations	PBF-LB, alloy and process development	Public funding Industry partners Application centre	
ORNL Advanced Manufacturing Program: https://www.ornl.gov/advancedmanufacturing	Oak Ridge National Laboratory	Material and process development, Industrialisation	PBF_EB, BJ, PBF-LB, DED,	Public and industrial funding	
Monash Centre for Additive Manufacturing https://platforms.monash.edu/mcam/	Monash University, Australia	Material and process development	PBF-LB, DED, HIP	Public funding, industrial partnership	

[3] Including various departments at RWTH, Fraunhofer ILT, Fraunhofer IPT, Access (12 R&D partners)

RAMP-UP Roadmap 2017 Short term



Roadmap

Activity start within 1-5 years

Prioritization scale
Low to high

Material
Understand and predict properties
Increase material portfolio
Methods for fast material development
Methods for material characterization
Tuning and tailoring of microstructure in AM-process

Part and system design
Develop design guidelines for AM-production and components
Design optimization (lightweight, faster printing etc.)
Design for AM full potential
IP&IT security

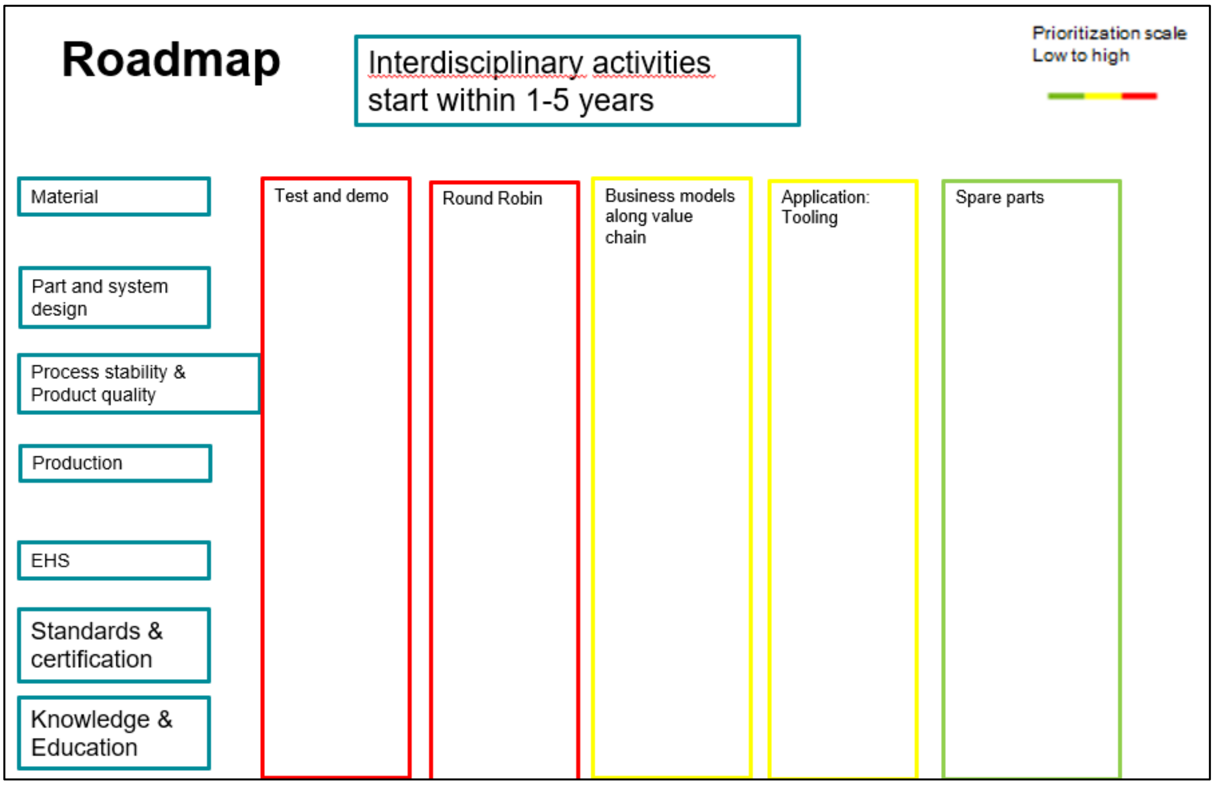
Process stability & Product quality
Reproducibility and robustness
In process control
Non destructive testing
Methods for fast process development
Methods for product verification
Process simulation incl. software
Less sensitive material handling in AM-machine and storage
Methods for geometrical assurance
Process and material predictability
Smart post processes developed for AM
Controlled recycling of powder material
Method for evaluation spreadability
Systems for quality assurance during production

Production
Drivers for AM/3DP
AM-machines in production systems incl. economical and technical feasibility
Productivity
Digitalization
Smart automation

Environment, health, safety
Powder handling- knowledge transfer
Safe usage of AM
Best working practice/guidelines
Sustainability of powder material
LCA
IT security

Standards & certification
Review existing standards and certifications
Needs of standards, input to SIS
Development of standards (SIS, own roadmap)

Knowledge & Education
Knowledge needs
Develop education for industry and academy –modular for different levels and areas
Design for AM
AM "know how"
Process understanding
Material knowledge
Automation knowledge



Roadmap

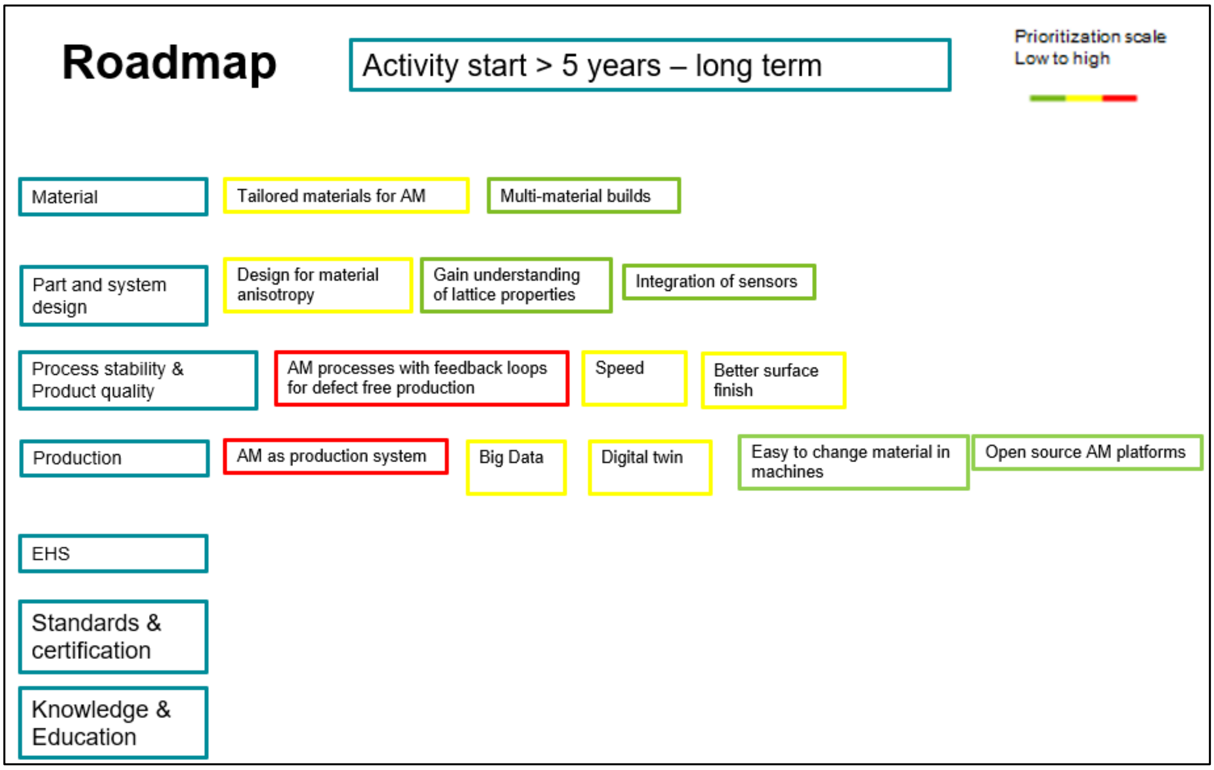
Interdisciplinary activities start within 1-5 years

Prioritization scale
Low to high

Material
Part and system design
Process stability & Product quality
Production
EHS
Standards & certification
Knowledge & Education

Test and demo
Round Robin
Business models along value chain
Application: Tooling
Spare parts

RAMP-UP Roadmap 2017 Long term



Roadmap

Activity start > 5 years – long term

Prioritization scale
Low to high
🟩🟨🟥

Material
- Tailored materials for AM
- Multi-material builds

Part and system design
- Design for material anisotropy
- Gain understanding of lattice properties
- Integration of sensors

Process stability & Product quality
- AM processes with feedback loops for defect free production
- Speed
- Better surface finish

Production
- AM as production system
- Big Data
- Digital twin
- Easy to change material in machines
- Open source AM platforms

EHS

Standards & certification

Knowledge & Education

Project list

Financing body	DNR	Project Title	Coordinator	Contribution, SEK	RAMP-UP classification
Vinnova	2020-04855	Kvalitetssäkring av Additiv Tillverkning för fabricering av storskaliga lättviktsstrukturer	Procada AB	125 000	Process Stability & Product Quality
	2020-04821	Swedish additive manufacturing testbed - Application Center for Additive Manufacturing (ACAM)	RISE IVF AB, div. material och produktion	1 000 000	Centra
	2020-04655	Additive Manufacturing European Digital Innovation Hub	Stiftelsen Chalmers Industriteknik	200 000	Overall
	2020-04339	SMF CAM2: FEM-baserad modell för stelning med speciell tillämpning för additiv tillverkning.	Thermo-Calc Software AB	800 000	Process Stability & Product Quality
	2020-04328	FuRAM Uppföljning av forskningsbehov för industrialisering av additiv tillverkning i metall	Swerim AB	600 000	Overall
	2020-04266	Ytbehandling och legeringsutveckling för reducerad vikt av AM aluminiumartiklar	Linköpings Universitet	3 350 000	Material
	2020-04259	Utveckling av additivt tillverkade kylkomponenter med mikro- och minikanaler	Lunds Universitet, energivetenskaper	4 000 000	Parts & System Design
	2020-04251	d-LIGHT: Designa lätt och snabbt - gröna gasturbiner baserat på innovativa lättviktslösningar	Linköpings Universitet	3 449 917	Parts & System Design
	2020-04247	Excellent fabricering av lättviktsstrukturer genom varmformning, svetsning och AM	Brogren Industries AB	3 000 000	Production
	2020-03794	Hard X-ray spectroscopy characterization of biocorrosion of additively manufactured Mg	Swerim AB, materialutveckling	499 000	Process Stability & Product Quality
	2020-03792	In-situ studie av korrosion egenskaper av additivt tillverkat rostfritt stål med normal trycks X-ray spektroskopi	Swerim AB, materialutveckling	500 000	Process Stability & Product Quality
	2020-03784	Spatially resolved X-Ray analysis of machining induced white layers	Lunds Universitet, institutionen för maskinteknologi	392 000	Process Stability & Product Quality

Financing body	DNR	Project Title	Coordinator	Contribution, SEK	RAMP-UP classification
Vinnova	2020-03782	In-situ Synchrotron Investigations of Additive Manufacturing parts for Ni-base Superalloys	Swerim AB, material- och processutveckling	499 000	Process Stability & Product Quality
	2020-02998	Additiv tillverkningslösning & industralisering för nästa generation komressormellanhus	GKN Aerospace Sweden AB, avd 9635 design engineering	4 552 943	Production
	2020-02997	DEMAND-REPAIR "Utveckling av avancerad tillverkningsteknik för reparation av nästa generations luftmotorer"	GKN Aerospace Sweden AB, R&T process engineering	4 230 021	Production
	2020-02908	3D-printad högfrekvent induktor till elfordon för både högre verkningsgrad och högre effekttäthet	Swerim AB, produktionsteknik	400 000	Process Stability & Product Quality
	2020-02492	Additiv tillverkning för fabricering av storskaliga lättviktsstrukturer	Procada AB	125000	Process Stability & Product Quality
	2020-02447	Värmebehandling av metallkomponenter för svensk flygindustri	Swerim AB	125000	Knowledge & Education
	2020-00828	MagNeutron - Texturanalysis, med neutrondiffraktion, av magnesiumlegeringar	Swerim AB. materialutveckling	384000	Process Stability & Product Quality
	2020-00808	Förbättrade egenskaper hos additivt tillverkade metaller genom tillsats av grafen	Mittuniversitetet	300000	Overall
	2020-00188	IntDemo Motor	GKN Aerospace Sweden AB	52 000 000	Standards & Certification
	2020-00187	IntDemo-Flygplan	SAAB AB Aeronautics	48 000 000	Production
	2019-05917	In-situ monitorering och reglering av additiv tillverkning för fabrikation av flygmotorkomponenter	Procada AB	325 000	Process Stability & Product Quality
	2019-05591	Demonstration of Infrastructure for Digitalization enabling industrialization of AM	Chalmers Tekniska Högskola	9 407 679	Production
	2019-05370	ALTOS - Aluminium Two O five Structures	GKN Aerospace Sweden AB	4 500 000	Parts & System Design
	2019-05363	SMF CAM2: Adaptrar för navigationssensorer till kirurgiska instrument	Lasertech LSH AB	150 000	Parts & System Design
	2019-05358	Lättare värmeväxlare genom additiv tillverkning	RISE IVF AB	325 000	Parts & System Design
	2019-05352	SMF CAM2: Processoptimering utav EBM processen för Ti6Al4V genom punktsmältning	Additive Innovation & Manufacturing Sweden AB (AIM)	250 000	Process Stability & Product Quality

Financing body	DNR	Project Title	Coordinator	Contribution, SEK	RAMP-UP classification
Vinnova	2019-05311	SMF CAM2: Adaptrar för navigationssensorer till kirurgiska instrument Summa	AIM Sweden AB	150 000	Production
	2019-05310	SMF CAM2: Adaptrar för navigationssensorer till kirurgiska instrument Summa	Ortoma AB	200 000	Production
	2019-05304	SCCAM - Residual stresses and SCC in additively manufactured stainless steel by neutron diffraction	Swerim AB	500 000	Process Stability & Product Quality
	2019-05287	Synkrotronstudie av sprickor i AM-byggda delar med laser-pulverbäddsfusion	Swerim AB, material- och processutveckling	498 000	Material
	2019-05276	In-situ X-ray diffraction study of additive manufacturing to aid in tool steel development	Kungliga Tekniska Högskolan, institutionen för materialvetenskap	500 000	Material
	2019-05261	Implementering av additiv tillverkning av metalliska komponenter i precisionsgjuterier	RISE IVF AB, additiv tillverkning	325 000	Process Stability & Product Quality
	2019-05259	MagLite Magnesiumkomponenter för lättviktstillämpningar medelst AM	Exmet AB	260 000	Process Stability & Product Quality
	2019-05066	SMF ECO2: Automatiserad urvalsprocess för Additiv Tillverkning	Yovinn AB	400 000	Knowledge & Education
	2019-04887	World Class Material II	Swerim AB	477 000	Material
	2019-04872	LAserdrivna Metalldroppar som möjliggör multimaterial 4D-printing (LAM-4D) - etapp 2	Luleå Tekniska Universitet	496 799	Process Stability & Product Quality
	2019-04815	SMF CAM2: Laser Metal Deposition as repair method (LERA)		247 500	Process Stability & Product Quality
	2019-03614	Kvantifiering av restaustenit i additivt tillverkade stållegeringar med hjälp av synkrotronljus	Kungliga Tekniska Högskolan, institutionen för materialvetenskap	299 000	Material
	2019-03584	Machining of AM components (MacAM)	Swerim AB	680 000	Knowledge & Education
	2019-02945	Spänningspåverkan och korrosionsegenskaper hos material framställda genom additiv tillverkning (SAMCO)	Swerim AB	3 898 500	Process Stability & Product Quality
	2019-02941	Funktionaliserade additivtillverkade varmformningsverktyg	Luleå Tekniska Universitet	3 000 000	Parts & System Design

Financing body	**DNR**	**Project Title**	**Coordinator**	**Contribution, SEK**	**RAMP-UP classification**
Vinnova	2019-02752	Processstyrning av additiv tillverkning med laser och tråd	GKN Aerospace Sweden AB, AVD 9634JA	4 060 000	Process Stability & Product Quality
	2019-02741	Utveckling av elektronstrålesmältningsprocessen med titan för tillverkning av framtida flygmotorkomponenter	GKN Aerospace Sweden AB, R&T PROCESS ENGINEERING	3 950 620	Process Stability & Product Quality
	2019-02638	Metalldeponering med additiv tillverkning - METTHRAM	Högskolan Väst	4 799 221	Parts & System Design
	2019-02631	Våga printa tunt	Swerim AB	4 280 000	Parts & System Design
	2019-02625	Accelererad Utveckling av Avancerade Höghållfasta Lättviktslegeringar för Selektiv Lasersmältning Process	RISE IVF AB, avdelning tillverkning	775 000	Material
	2019-02618	Generisk partikelmodell för FEM kopplad till Calphad-metoden för ingående data	Kungliga Tekniska Högskolan	1 799 627	Material
	2019-02607	Utveckling av EBM-tillverkad titanlegering delar för högpresterande lättviktdesign	Chalmers Tekniska Högskola	3 600 000	Process Stability & Product Quality
	2019-02584	Detektering av töjning-åldringssprickor med diffraktion- och tomografiexperiment	Malmö Universitet, fakulteten för teknik och samhälle	495 000	Process Stability & Product Quality
	2019-02564	Fasförändringar i additivt tillverkade komponenter	Höganäs AB	500 000	Material
	2019-02502	Infrastructure for Digitalsation enabling industrialization of Additive manufacturinG - IDAG	Chalmers Tekniska Högskola	495000	Knowledge & Education
	2019-02138	Additiv tillverkning av metallkomponenter förstärkta med grafen - Addit-G	Swerim AB	1109960	Material
	2019-01087	Möjliggöra tillväxt av metallpulverförsäljning, genom standardisering av flytbarhet	Kungliga Tekniska Högskolan	734 791	Standards & Certification
	2019-01080	Standardisering inom additiv tillverkning av metall	Swerim AB	1 000 000	Standards & Certification
	2019-00786	Flexibel additiv tillverkning av komponenter för millimeter och mikrometervågor	Chalmers Tekniska Högskola	3 600 000	Parts & System Design
	2019-00779	ROBust Optimering i Design för Additiv Tillverkning (ROBODAM)	Örebro Universitet, akademin för naturvetenskap och teknik	4 995 981	Parts & System Design

Financing body	DNR	Project Title	Coordinator	Contribution, SEK	RAMP-UP classification
	2019-00029	Additiv Tillverkning för Livsvetenskaperna	Uppsala Universitet	32 788 690	Centra
	2018-05292	Innovativa Pulverkomponenter via Additiv Tillverkning - Globalinitiativ	Chalmers Tekniska Högskola	4 750 000	Overall
	2018-04995	SMF CAM2: Optimized fixtures through metal additive manufacturing (3d-Fix)	Cascade Control Ab	150 000	Process Stability & Product Quality
	2018-04888	SMF CAM2: Optimized fixtures through metal additive manufacturing (3d-Fix)	Brogren Industries AB	850 000	Knowledge & Education
	2018-04737	Demonstration och kunskapsspridning av nationella testbäddar inom additiv tillverkning	RISE IVF AB, avdelningen för tillverkning	500 000	Knowledge & Education
	2018-04591	Doktorand - Användning av nya optiska och avbildande tekniker för ytstruktur karakterisering	RISE Research Institutes of Sweden AB, RISE Mätteknik	300 000	Process Stability & Product Quality
	2018-04444	Framtidens fabrik för AM och komposit - OGV-Demonstrator (FAMKO)	GKN Aerospace Sweden AB	9 000 000	Production
	2018-04432	In-situ neutron/synkrottron studie av mikrostrukturens utveckling i AM verktygsstål	Uddeholm AB	500 000	Process Stability & Product Quality
	2018-04324	LAM-4D - Laserdrivna metalldroppar som möjliggör multi-material 4D-printing	Luleå TU	500 000	Production
	2018-04312	RapikKAT - Radikalt ökad produktivitet genom innovativt designade kylkanaler tillverkade med AM	RISE, Borås	499 616	Parts & System Design
	2018-04311	Amexci Safe by design	Alfred Nobel Science Park	500 000	Parts & System Design
	2018-04283	World Class Material	Swerim AB	500 000	Material
	2018-03910	AMCO-Säker användning av AM rostfria stålprodukter i korrosiva miljöer	Swerim AB	2 289 618	Process Stability & Product Quality
	2018-03336	HÄMAT2 - Hälso- och miljöpåverkan orsakad av AM och utmaningar för en hållbar produktion - 2	Swerim AB	9 997 120	Environment, Health & Safety
	2018-02987	Framtagning av verktyg för tillverkning av AM förstärkt titandetalj	RISE IVF AB	325 000	Production

Financing body	**DNR**	**Project Title**	**Coordinator**	**Contribution, SEK**	**RAMP-UP classification**
Vinnova	2018-02849	Graderad AM-högtemperaturlegering	Swerim AB	800 000	Material
	2018-02844	Lättare komponenter genom AM av Al-legeringar	RISE IVF AB	5 140 000	Parts & System Design
	2018-02597	MoSi2-baserat material tillverkat via SLM för korrosions/erosions komponenter i gasturbiner	Chalmers Tekniska Högskola	1 000 000	Material
	2018-00815	Design av en högpresterande amorf legering för additiv tillverkning	QuesTek Europe AB	2 712 139	Material
	2018-00809	Applikationsdriven utveckling för ökad robusthet och pålitlighet i additiv tillverkning av metall	Swerea KIMAB AB	5 737 693	Process Stability & Product Quality
	2018-00805	Materialdesign för additiv tillverkning av industriella verktyg	Swerea KIMAB AB	5 810 000	Material
	2018-00804	Nya materiallösningar för defektfri additiv tillverkning av svårsvetsade Ni-baserade legeringar	Linköpings universitet	5 000 000	Material
	2018-00803	Design av Nya Material och Processer för Nästa Generations Additiv Tillverkning	Kungliga Tekniska Högskolan	6 330 000	Material
	2018-00801	Industrialisering av additiv tillverkning genom multifunktionell efterbearbetning	Mittuniversitetet	4 880 804	Production
	2018-00800	Hållbar tillverkning av 3D-printade sandformar och -kärnor	Swerea SWECAST AB	1 730 000	Production
	2018-00799	Kontroll av pulver och processvariationer för en robust och repeterbar additiv tillverkning i metall	Swerea IVF AB	4 444 150	Process Stability & Product Quality
	2018-00798	Design och materialprestanda för lättvikt vid pulverbäddbaserad additiv tillverkning	Chalmers Tekniska Högskola	4 650 000	Parts & System Design
	2018-00794	Utbildning i produktion av metallpulver – Framtidens arbetskraft i Sverige	Kungliga Tekniska Högskolan	883 278	Knowledge & Education
	2018-00754	Ökad funktionalitet av metalliska material från additiv tillverkning genom ytmodifiering	Uppsala universitet	186 000	Process Stability & Product Quality
	2018-00511	Industriell transformation genom digitalisering baserad på 3D-printning av metaller (Digi3D-skiftet)	Örebro universitet	808 823	Production

Financing body	**DNR**	**Project Title**	**Coordinator**	**Contribution, SEK**	**RAMP-UP classification**
Vinnova	2018-00491	Smarta MetalLyftet	Swerea SWECAST AB	500 000	Knowledge & Education
	2018-00485	Planering av testmiljö för visualiserad tillståndsmätning av komponenter via integrerad fiberoptik	Swerea IVF AB	500 000	Process Stability & Product Quality
	2017-05135	Koordinering av forskning inom additiv tillverkning av metall	Swerea KIMAB AB	1 500 000	Overall
	2017-04856	Adaptiv oförstörande provning vid additiv tillverkning	GKN Aerospace Sweden AB	5 468 557	Process Stability & Product Quality
	2017-04850	Additiv tillverkning av högtemperaturmaterial och utvärdering av svetsbarhet	GKN Aerospace Sweden AB	2 830 001	Process Stability & Product Quality
	2017-04847	Defekt prediktering för laser metall deponering av Ti-6Al-4V tråd	GKN Aerospace Sweden AB	2 739 764	Process Stability & Product Quality
	2017-04846	SUDDEN- Ytfenomen och defekters påverkan på mekaniska egenskaper hos additivt tillverkad Ti-6Al-4V	GKN Aerospace Sweden AB	6 958 000	Process Stability & Product Quality
	2017-04799	Hållbart utnyttjande av metallpulver i pulverbäddsbaserad additiv tillverkning	Stiftelsen Chalmers Industriteknik	500 000	Process Stability & Product Quality
	2017-04796	Effektivt cirkulationssystem för material i additiv tillverkning	Stiftelsen Chalmers Industriteknik	500 000	Environment, Health & Safety
	2017-04776	Digitalisering av tillverkningsflödet av Additiv Tillverkning I Sverige	Swerea IVF AB	7 126 400	Production
	2017-04261	Högre kvalité på lätta konstruktionsdetaljer tillverkade via Additiv Tillverkning	Swerea IVF AB	500 000	Process Stability & Product Quality
	2017-02531	Ny processteknik för medelserieproduktion av heltäta pulvermetallurgiska material och komponenter	Chalmers Tekniska Högskola	800 000	Production
	2017-01950	Uppkoppling och tillståndsmätning av 3D-tillverkade komponenter i krävande applikationer	Swerea IVF AB	6 350 000	Process Stability & Product Quality
	2017-01636	Digitalisering av AM-produktionskedjan för att skapa effektivitet	Swerea KIMAB AB	3 550 000	Production

Financing body	**DNR**	**Project Title**	**Coordinator**	**Contribution, SEK**	**RAMP-UP classification**
Vinnova	2017-01495	Tools and methods for certification of AM fabricated parts for aerospace applications	Swerea KIMAB AB	250 000	Knowledge & Education
	2017-01265	Innovativ pulverbaserad komponentteknologi (INNOKOMP)	Chalmers Tekniska Högskola	5 970 000	Material
	2017-01256	Hälso-och miljöpåverkan av additiv tillverkning och dess utmaningar för en hållbar produktion- HÄMAT	Swerea KIMAB AB	500 000	Environment, Health & Safety
	2017-00544	Metal Paste - Utveckling av en metod för additiv tillverkning i metall	BRYNE AB	300 000	Production
	2016-05418	ReLed-3D Resurseffektiv och flexibel produktion inom fordonsindustrin genom additiv tillverkning i metall	Swerea IVF AB	3 749 000	Production
	2016-05267	Framtida direkttillverkade metallstrukturer (DirektMetall)	Jernkontoret	2 481 000	Overall
	2016-05175	Kompetenscentrum för additiv tillverkning - metall	Chalmers Tekniska Högskola	36 000 000	Centra
	2016-04486	Snabbare introduktion av additiv tillverkning genom digitaliserad kvalitetssäkring och digitala produktlager	Swerea IVF AB	3 377 500	roce
	2016-04384	Verifierad digital optimeringsarena för verktygsproduktion genom 3D-metallprintning	Örebro universitet	4 000 000	Production
	2016-03972	Uppkoppling och tillståndsmätning av 3D-tillverkade komponenter i krävande application	Swerea IVF AB	500 000	Process Stability & Product Quality
	2016-03898	Färdplan för forskning och innovation för industrialisering av additiv tillverkning av metaller i Sverige	Swerea KIMAB AB	3 000 000	Overall
	2016-03305	Additivt tillverkade verktygsdelar för flexibel produktion och optimerade produktegenskaper	Swerea IVF AB	4 750 000	Production
	2016-03290	Flexibel tillverkning av funktionella kopparbaserade produkter	Chalmers Tekniska Högskola	3 150 000	Production
	2016-02675	Nytt nickelbaserat material för additiv tillverkning av komponenter för högtemperaturapplikationer	Chalmers Tekniska Högskola	2 000 000	Material
	2016-01990	Återvinningsstudie av metallpulver för AM	Swerea KIMAB AB	1 000 000	Environment, Health & Safety

Financing body	DNR	Project Title	Coordinator	Contribution, SEK	RAMP-UP classification
Vinnova	2016-01968	Digitalisering av komplett produktionsflöde en förutsättning för additiv tillverkning (DINA)	Swerea SWECAST AB	4 000 000	Production
	2016-01925	Additiv Tillverkning av Komplexa Keramiska Kärnor för Percisionsgjutning	Swerea IVF	414 000	Production
	2015-05830	Kompetensutveckling inom optimering av EBM-teknologin	SP SVERIGES TEKNISKA FORSKNINGSINSTITUT AB	150 000	Knowledge & Education
	2015-05086	Högpresterande lättviktskomponenter genom additiv tillverkning	Swerea KIMAB	5 000 000	Parts & System Design
	2015-03989	Test- och demonstrationsanläggning för geometriskt komplexa komponenter till flygindustrin (ToD Cast)	Swerea SWECAST AB	600 000	Knowledge & Education
	2015-03457	Pulver och materialdesign för flexibel addtiv tillverkning av högpresterande komponenter	Chalmers Tekniska Högskola	4 610 000	Material
	2015-03449	Modelleringsstödd Materialutveckling för Additiv Tillverkning och nya Pulverstål	Swerea KIMAB	649 000	Material
	2015-03447	Utveckling av nästa generations verktyg genom additiv tillverkning - Steg 2	Swerea SWECAST AB	2 880 000	Parts & System Design
	2015-03444	Utvärdering av metod för gjutinfiltrering av järnpulver (P-cast).	Swerea SWECAST AB AB	461 000	Production
	2015-02285	Additiv tillverkning med pulver som tillsatsmaterial	GKN	1 500 000	Production
	2014-05148	Optimerad produktionsprocess för additiv tillverkning	SP	5 400 000	Parts & System Design
	2014-01830	Nya generationens verktyg genom additiv tillverkning (ADDING)	Swerea SWECAST AB	996 295	Production
	2014-00795	Innovativ komponentteknologi via pulverteknik	Chalmers	8 000 000	Material
	2013-04686	Additivt tillverkade verktyg för skärande bearbetning	VBN Components	3 304 000	Production
	2013-03645	Tribologisk provning av additivt tillverkat material för bränsleventil	VBN Components	457 750	Material
	2012-03789	Systematiserad prototypframtagning för ökad konkurrenskraft (SPÖK)	Swerea SWECAST AB AB	500 000	Production

Financing body	**DNR**	**Project Title**	**Coordinator**	**Contribution, SEK**	**RAMP-UP classification**
Vinnova	2012-02520	Additiv tillverkning av fordonskomponenter	Högskolan Väst	500 000	Production
	2011-03413	Plattform för direkttillverkning av mikrokomponenter	Swerea IVF	4 000 000	Production
KK	20200200	Bitr. lektor i produktionsteknik inriktning additiv tillverkning	Högskolan Väst	2 598 198	Knowledge & Education
	20200198	Adjungerad lektor, Additiv tillverkning, Sandvik	Högskolan Väst	2 047 635	Knowledge & Education
	20200197	Adjungerad lektor, Additiv tillverkning, ARCAM	Högskolan Väst	964 844	Knowledge & Education
	20200143	PROF-AM Internationell gästprofessor i additiv tillverkning	Mittuniversitetet	337 820	Knowledge & Education
		Cracking criteria for welding and welding based AM	Högskolan Väst	492 000	Process Stability & Product Quality
	2019 Forskningsprofiler	PODFAM – Pulverbäddsbaserad additiv tillverkning av metallkomponenter för gasturbinapplikationer	Högskolan Väst	49 200 000	Production
	2019 Prospekt	LasReX – Lasermetalldeponering med Hastelloy X pulver för reparation av lastbärande gasturbinkomponenter	Högskolan Väst	2 460 000	Production
	2019 Synergi	AMHIPP - Avancerade material för högpresterande produkter	Karlstad Universitet	14 400 000	Material
	2019 HÖG	Nanosafety - Hälsoeffekter av partiklar från additiv tillverkning	Örebro Universitet	4 075 727	Environment, Health & Safety
	2018	Synergi - Svetsbaserad additiv tillverkning	Högskolan Väst	12 300 000	Production
	2018	Prospekt - Förbättrad sprickprogagering av exponerad superlegering tillverkad genom AM	Högskolan Väst	2 460 000	Process Stability & Product Quality
	2018	Rekrytering - Rekrytering gästprofessor i svetsbaserad AM av superlegeringar	Högskolan Väst	369 000	Knowledge & Education
	20170060	Synergi - Utveckling av additiv tillverkning med laser och tråd för tillverkning av högpresterande komponenter	Högskolan Väst	14 197 158	Process Stability & Product Quality
	20160327	HÖG - Tooladdict - Konkurrenskraftig framtagning av verktyg med additiv tillverkning	Stiftelsen Högskolan i Jönköping	4 338 087	Production

Financing body	**DNR**	**Project Title**	**Coordinator**	**Contribution, SEK**	**RAMP-UP classification**
KK	20160281	Forskningsprofil+ Hv SUMAN-Next	Högskolan Väst	18 000 000	Centra
	20140153	Avancerade verktyg genom additiv tillverkning	Örebro universitet	2 437 001	Production
SEM	P48716-1	Effektiv kombinatorisk design av mjukmagnetiska metallglas för additiv tillverkning	Uppsala Universitet	5 000 000	Material
	P48303-1	Design, optimering och tillverkning av högeffektiva värmeväxlare tillverkade med 3D-printing	Kungliga Tekniska Högskolan	3 563 000	Parts & System Design
	P44135-1	Multifysiktopologioptimeringsmetoder för design av gasturbinkomponenter genom additiv tillverkning	Linköpings Universitet	2 585 435	Parts & System Design
	P44112-1	Prediktering av utmattningslivslängd hos additivt tillverkade duktila superlegeringar	Linköpings Universitet	3 622 254	Process Stability & Product Quality
	P40354-1	Resurseffektiv tillverkning av nya högpersterande slitstarka material	VBN Components	4 079 700	Production
	P38365-1	Energieffektiva magnetiska material för elektrifierade fordon	Exmet AB	350 000	Material
SSF	FID 17-0028	Forskarutbildning inriktning mot Mg	Swerim AB	2 500 000	Material
	FID 17-0015	Forskarutbildning inriktning mot Al	RISE IVF	2 500 000	Process Stability & Product Quality
	ID15-58	Matematik för elektronstrålesmältning i 3D-skrivning i metall	Chalmers Tekniska Högskola	2 500 000	Production
	GMT15-48	Utveckling av processer och material i additiv tillverkning	Uppsala universitet	32 500 000	Process Stability & Product Quality
	ID14-60	Additiv tillverkning:Skadetålighet hos flygkristiska artiklar	Linköpings Tekniska Universitet	2 500 000	Process Stability & Product Quality
	vdb15-5	Människa o maskin	Tekniska Museet	100 000	Knowledge & Education
	PV10-64	Antibakteriella kronor och broar tillverkade via EBM	Uppsala universitet	0	Production

Financing body	DNR	Project Title	Coordinator	Contribution, SEK	RAMP-UP classification
TVV Regional ERUF		Förstudie förstärkt arena produktions-teknisk utveckling	Innovatum	300 000	Centra
		Springboard	Innovatum	10 600 000	Production
	ID 20201538	RepLab - Reparation och återanvändning av metallprodukter inom AM	Högskolan Väst	8 800 000	Production
		Etableringsprojekt: Test- o demomiljö AM	RISE IVF	1 500 000	Centra
	2020-233	Etablera smart industricenter Värmland i Hagfors	Hagfors kommun	2 121 276	Centra
	202010189	AM Förstudie	Region Örebro Län	1 471 000	Overall
	2020-46, 20204910	ADDIFAB - Den additiva digitalstödda ide´fabriken 4.0	Luleå Tekniska Universitet	8 059 612	Overall
	2019-32	I2P-From Idea to Printing of Metal Products	Luleå Tekniska Universitet	4 535 151	Knowledge & Education
	2020-31	DAMI 4.0 Etablering	Karlstad Universitet	482 123	Centra
	2020-4039	AM on the road	Sandvikens kommun	400 000	Centra
	2019-30, 2024059	Förstudie: Centrumbildning inom avancerad industri på Högskolan Dalarna	Högskolan Dalarna	697 294	Centra
	2019-18, 20202768	Förstudie Material X & AM i Uppsala	Region Uppsala	600 000	Overall
	20203076	AM Nordic	Alfred Nobel Science Park	130 000	Overall
	2019-2	ACES - Additive Coordination in East middle Sweden	Alfred NobelScience Park	1 121 218	Centra
	2018001603	Smart industri i norra mellansverige II	Region Gävleborg	6 821 896	Overall
	ID 20201562	TROJAM - 3DC Tröndelag - Jämtland 3D center AM metall	Mittuniversitetet	2 623 649	Centra
	2018-406,	Utbildning genom AM	Hagfors Kommun	200 000	Knowledge & Education
	201800084	SpaceLab - Del av HV strategi att skapa nationell arena för AM	Högskolan Väst	9 708 000	Centra
	201700880	RepLab - AM tekniker inom återtillverkning och reparation	Högskolan Väst	20 000 000	Production

Financing body	DNR	Project Title	Coordinator	Contribution, SEK	RAMP-UP classification
TVV Regional ERUF	2017000147	HybrAM - Hybridkomponent genom AM	Örebru Univ	500 000	Production
	C3TS	Arctic platform to create, 3D-print, test and sell	Luleå Tekniska Universitet	3 878 451	Centra
	2016-363, 195184,	AT-Lab - Regionalt lab för AM vid Karlstad Univ	Karlstad universitet	6 925 112	Centra
	201601594	3DPrintPlus - Samverkansprojekt med syfte att etablera en förstärkt AM-platform	Chalmers Tekniska Högskola, Högskolan Väst	9 600 000	Centra
	612-0801-15	3D Print - Investering i EBM	Högskolan Väst	16 000 000	Centra
	201600021	Utbildningspilot AM	Alfred Nobel Science Park	150 000	Knowledge & Education
	3DTC	TTC kluster inom AM och 3D-röntgen	Alfred Nobel Science Park	9 602 214	Centra
	ID 20200328	MapLab - AM med laserdeponering av pulver	Högskolan Väst	16 000 000	Process Stability & Product Quality
	303-2872-15,	CMT - Nordic business opportunities from coating and AM	Luleå Tekniska Universitet	2 392 722	Overall
	ID168796	Additiv tillverkning som konkurrensfördel	Mittuniversitetet	1 700 000	Production

Financing body	DNR	Project Title	Coordinator	Contribution, Euro	RAMP-UP classification
EU	Top AM	Tailoring ODS materials processing route for additive manufacturing of high temperature devices for aggressive environments	RISE IVF, Questek Europé AB, Sandvik Mat. Techn.	954 955	Material
	NUCOBAM	Nuclear Components Based on Additive Manufacturing	Ramen Valves AB	39 235	Standards & Certification
	SoftDREAM	Software tools for hybrid robot based AM for industrial applications	RISE IVF, RISE Sicomp, Spectrum Technology	380 000	Production
	DigiQUAM	Digitalization of in-line QA for AM	RISE IVF, Chalmers	148 000	Production
	SAMOA	Sustainable Al additive manufacturing for high performance applications	Luleå tekniska Universitet	2 800 000	Material
	INNOADDITIVE	Innovation Challanges for Additive Manufacturing	LTU Business	0	Overall
	ENABLE	European network for alloys behaviour law enhancement	Luleå Tekniska Universitet	527 319	Material

Financing body	DNR	Project Title	Coordinator	Contribution, SEK	RAMP-UP classification
EU	MANUELA	AM using metal pilot line	Chalmers, IVF	4 533 418	Production
	INTEGADDE	Intelligent data-driven pipeline for the manufacturing of certified metal parts through DED processes	Högskolan Väst	1 812 313	Production
	INEX-ADAM	Increasing Excellence on Advanced AM	Lunds Universitet	214 675	Overall
	SPAcEMAN	Sustainable Powders for AM	Luleå Tekniska Universitet	No info	Material
	AddMan	Innovative re-design and validation of complex airframe structural components formed by AM for weight reduction	Linköpings Tekniska Universitet	575 166	Process Stability & Product Quality
	AMOS	AM optimization and simulation platform for repairing and re-manufacturing of aerospace components	GKN Aerospace	490 000	Environment, Health & Safety
	EBM Perform	High-quality, high-speed EBM 3D printing by the integration of high-performance electron sources	Arcam AB	1 648 035	Process Stability & Product Quality
	TIALCHARGER	TiAlN turbochargers - improved fuel economy reduced emissions	Arcam AB	168 392	Parts & System Design
	AMAZE	Aiming towards zero waste & efficient production of high-tech metal products	Volvo Technology	149 625	Production
	HYPROLINE	High performance production line for small series metal parts	Fcubic-DigitalMetal, Swerea IVF	813 859	Process Stability & Product Quality
	SASAM	Support action for standardisation in AM	SIS	9 615	Standards & Certification
	MERLIN	Development of aeroengine component manufacture using laser AM	GKN Aerospace, HV	716 979	Production
	HIRESEBM	High resolution EBM	Arcam AB	352 765	Production
	FASTEBM	High productivity EBM AM development for the part production systems market	Arcam AB	452 729	Production
	KARMA	Knowledge based process planning and design for additive layer manufacturing	Mittuniversitetet	13 228	Parts & System Design

Financing body	DNR	Project Title	Coordinator	Contribution, SEK	RAMP-UP classification
AFA	150246	Kartläggning av metall-partikelexponering samt möjliga hälsoeffekter vid professionellt arbete med 3D-skrivare.	Landstinget Östergötland	1 477 000	Environment, Health & Safety
ESA	G61A-018QT	ESA AM powder material supply chain: verification and validation	Swerim AB	5 002 794	Material
VR	2019-06068	Realtidsmätningar av additiv tillverkning med elektronstrålesmältning	Kungliga Tekniska Högskolan	7 980 000	Process Stability & Product Quality

Vinnova = Sweden´s Innovation Agency

KK = Knowledge Foundation

SEM = Swedish Energy Agency

SSF = Swedish Foundation for Strategic Research

TVV = Swedish Agency for Economic and Regional growth

ERUF = European Regional Development Fund

AFA = AFA Insurance

ESA = European Space Agency

VR = Swedish Research Council

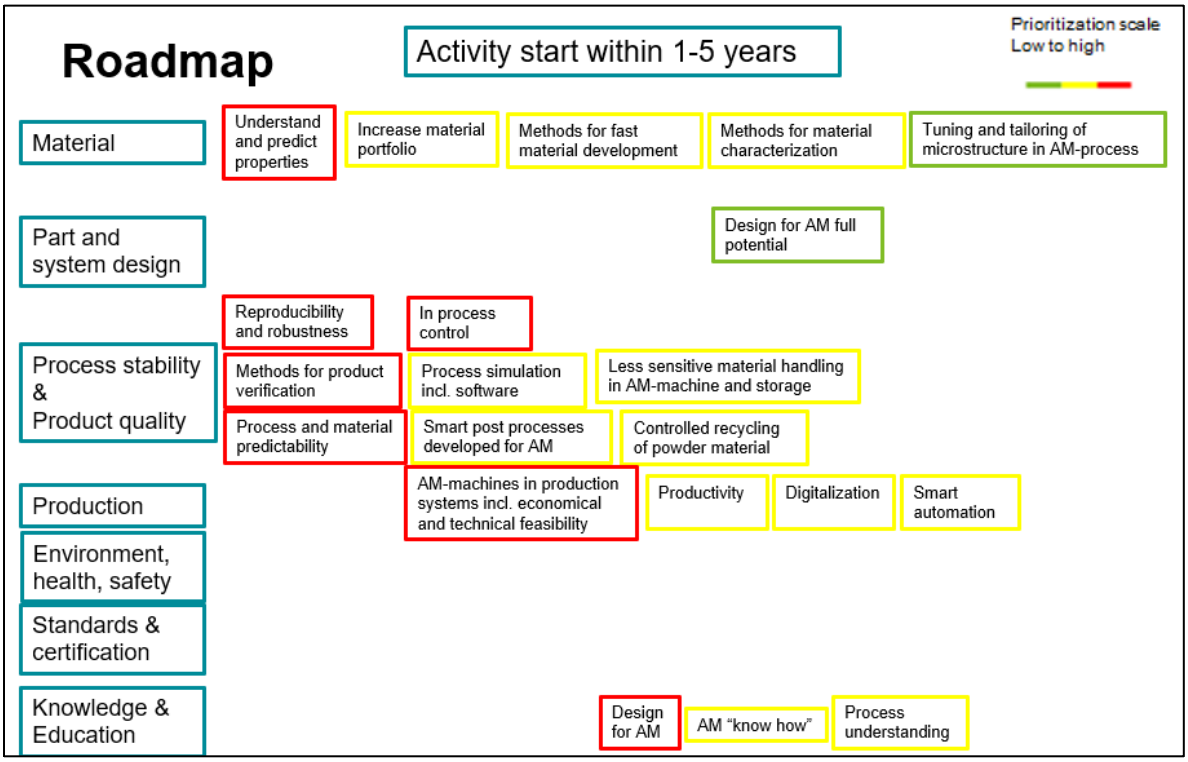
Projects listed under TVV/Regional/ERUF may have ERUF as well as regional funding. For those projects, contributions from different financing bodies have been added together.

In 2018, Swerea was merged into RISE and Swerim. The projects coordinated by Swerea KIMAB were shifted to Swerim and the project coordinated by Swerea IVF and Swerea SWECAST were transferred to RISE.

More information about the projects can sometimes be found on the webpages of the funding agencies or in the database Swecris: https://www.vr.se/swecris.html#/.

Highlighted priorities in the RAMP-UP roadmap

In spring 2021, many companies said that activities related to <u>all</u> RAMP-UP challenges within the seven areas were still important. Some companies highlighted specific challenges and those are shown in below.



Roadmap

Activity start within 1-5 years

Prioritization scale
Low to high
🟩🟨🟥

Material
- 🟥 Understand and predict properties
- 🟨 Increase material portfolio
- 🟨 Methods for fast material development
- 🟨 Methods for material characterization
- 🟩 Tuning and tailoring of microstructure in AM-process

Part and system design
- 🟩 Design for AM full potential

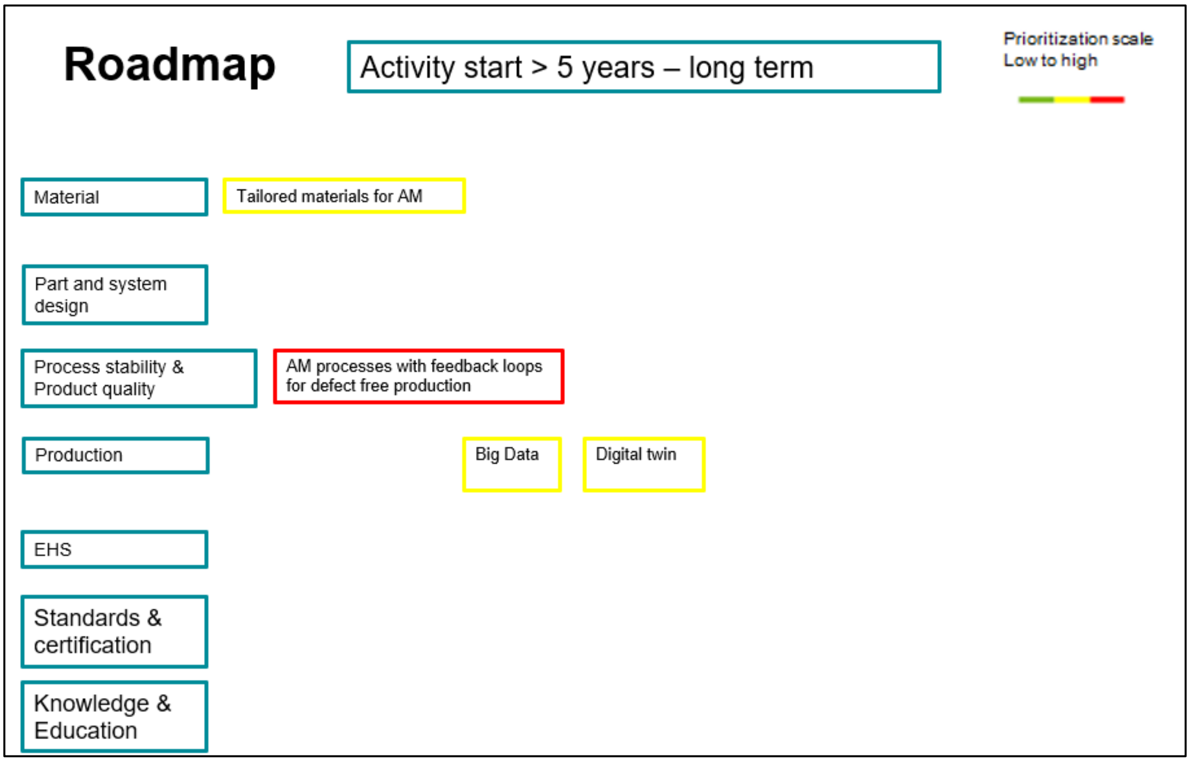
Process stability & Product quality
- 🟥 Reproducibility and robustness
- 🟥 In process control
- 🟥 Methods for product verification
- 🟨 Process simulation incl. software
- 🟨 Less sensitive material handling in AM-machine and storage
- 🟥 Process and material predictability
- 🟨 Smart post processes developed for AM
- 🟨 Controlled recycling of powder material

Production
- 🟥 AM-machines in production systems incl. economical and technical feasibility
- 🟨 Productivity
- 🟨 Digitalization
- 🟨 Smart automation

Environment, health, safety

Standards & certification

Knowledge & Education
- 🟥 Design for AM
- 🟨 AM "know how"
- 🟨 Process understanding



Roadmap

Activity start > 5 years – long term

Prioritization scale
Low to high
🟩🟨🟥

Material
- 🟨 Tailored materials for AM

Part and system design

Process stability & Product quality
- 🟥 AM processes with feedback loops for defect free production

Production
- 🟨 Big Data
- 🟨 Digital twin

EHS

Standards & certification

Knowledge & Education