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Statement

Additive Manufacturing

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Additive Manufacturing

Foreword

The term “Additive Manufacturing” refers to the production of parts by building up successive layers of a formless material such as metal powder. This makes it possible to “print” objects with a wide variety of different shapes. While the manufacture and utilisation of the relevant equipment and materials remains a young industry, it is already experiencing high growth rates even though the technologies are still developing. The expectations – particularly for industrial applications of Additive Manufacturing – are correspondingly high, in some cases perhaps even excessively so.

The German National Academy of Sciences Leopoldina, acatech – National Academy of Science and Engineering and the Union of the German Academies of Sciences and Humanities have established two working groups in order to gain an overview of the extremely wide and diverse field of Additive Manufacturing research with a view to formulating recommendations for its ongoing development. Under the overarching theme of “Additive Manufacturing”, the two groups are investigating the opportunities and challenges of this new technology from a variety of different perspectives.

For this initial statement entitled “Additive Manufacturing”, which focuses on industrial production, value networks and business models acatech acted as the lead institution. It addresses both the status quo and anticipated future developments: what role will Additive Manufacturing techniques play in the digital, connected industrial production of the future? Will this technology revolutionise industrial manufacturing? What impact will Additive Manufacturing have on value creation? And what recommendations can be formulated for government, industry and academia?

The working group led by Leopoldina is focusing on the specific basic research required in different disciplines to enable further development of Additive Manufacturing technologies. Its statement will also take an in-depth look at potential future Additive Manufacturing applications in fields such as medicine, food and construction, with regard to socially relevant issues relating to the workplace, safety and regulation.

The two working groups discuss their work with each other on a regular basis and regard their statements as two sides of the same coin. Our sincere thanks go to the members of both groups and to the reviewers for their contributions to this statement.

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Contents

1 Summary

Whether it is prosthetic hands, entire cars or even human clones, the things that industrial 3D printing might be capable of producing is a topic that has captured the imagination of economic forecasters, the media and science fiction writers alike. The boundaries between fact and fiction are blurred and expectations are often exaggerated. Additive Manufacturing, also known as industrial 3D printing, is in some respects still in its infancy. Nevertheless, it is continuously maturing – it has a huge range of potential applications and the industry has been achieving growth rates in the region of 30 percent for some years now. In 2015, it recorded global sales of 4.5 billion euros. Additive Manufacturing technologies will play an important role in tomorrow's digital, connected industrial production. For the foreseeable future, however, Additive Manufacturing is not expected to revolutionise production either technologically or in terms of value creation.

The term "Additive Manufacturing" refers to the production of parts by building up successive layers of a formless material. This makes it possible to "print" objects with a wide variety of different shapes. Additive Manufacturing operates vastly autonomous on the basis of digital 3D models. It comprises three stages: data preparation, the actual layer-by-layer building of the object and post-processing. A number of different joining methods and materials – e.g. plastics, metals or composites – may be employed, potentially in different combinations depending on the desired product attributes. The most commercially important techniques include Fused Deposition Modelling™ and Selective Laser Melting™. The former soon became widely adopted after its patent expired in 2009, sparking a surge of interest in Additive Manufacturing. Whether a particular technology is best suited to home use, simple workshops or factories also depends on the investment cost of the equipment, which can be anywhere between 500 and over 1 million euros.

When Additive Manufacturing began to be used in the 1990s, it was initially employed for prototyping (primarily in the automotive industry) and subsequently to make casting moulds and tools. Today, it is also used to make end products including small parts, small batches and one-off items for the jewellery or medical and dental technology industries.

Additive technologies differ from conventional manufacturing technologies in several respects and have huge potential if deliberately used with respect to their specific features. Their most important benefit is their high design flexibility. Since the material is built up layer by layer until the object is produced, there is no need for moulds, which are both time-consuming and costly to make. This means that it is theoretically possible to produce any shape. The actual degree of design flexibility depends on the method used and the specific shape of the item in question. For instance, some technologies require the use of support structures that must be removed once the build is complete. In the field of medicine, Additive Manufacturing makes it possible to tailor products such as dental implants, in-the-ear hearing aids or surgical aids to patients' individual anatomy. For many geometrically complex designs and shapes, the only alternative to Additive Manufacturing would be to create them by hand. Additive Manufacturing's greater dimensional accuracy and shorter production time are also an advantage for prototyping. Nevertheless, Additive Manufacturing technologies are not yet cost-effective enough for the mass production of simple, low value-added parts and are thus unsuitable for this purpose. The ability to make a finished product in one single manufacturing step is also likely to remain little more than a vision for some time to come.

It is in the context of mass customisation that Additive Manufacturing technology can really come into its own, since it allows products to be fully customised. It is thus a key enabler of smart, connected manufacturing concepts which characterise Industrie 4.0, where product planning is focused on the customer and their individual requirements. Additive Manufacturing technologies make it possible to produce very small series down to a batch size of one without significantly adding to the cost. For instance, one US sporting goods manufacturer is now using its customers' biomechanical data to produce running shoe soles tailored to their individual running style. However, the fact that post-processing of the finished product is still relatively laborious means that the mass production of individually customised items remains the exception for the time being.

Industrie 4.0 also calls for more flexible production processes. Additive Manufacturing makes it possible for parts to be made close to the place where they are used – the primary thing that needs to be distributed to the manufacturing location is the data. All spare parts processes could benefit from this decentralised manufacturing approach, since it would mean that replacement parts could be made wherever they are needed. In the space industry, large parts could in future be made in space, eliminating the expense of having them "delivered" by shuttles. However, even though they have been made using the same data, there is often still too much variability in the properties of additively manufactured parts. We do not yet have robust machines and manufacturing processes capable of delivering reproducible output.

One significant development in the field of Additive Manufacturing is process chain digitalisation, which is spurring the development of new business models and services. Online platforms make it possible to establish a marketplace e.g. for 3D CAD models, material formulae and process parameters which can be obtained either via a one-off download and purchase or via a streaming subscription in much the same way as digital music or films. However, a number of data security, copyright and standardisation issues still need to be resolved. International norms are also currently lagging behind the reality on the ground. A great many different Additive Manufacturing technologies now exist side by side, the terminology employed is often unclear and various trademarked names are used for processes that are in some cases identical. Additive Manufacturing also has the potential to support resource efficiency in future industrial production, although more still needs to be done to assess its economic, environmental and societal impacts in a holistic manner.

Additive Manufacturing will not revolutionise industrial production. However, there is good reason to believe that it will augment established methods in many different areas. In order to fully leverage the technology's economic and environmental potential for the German economy, it will be necessary to take concerted action in the areas of research, implementation, education and funding:

Research

1) In order to improve the productivity of Additive Manufacturing and reduce its drawbacks compared to conventional manufacturing technologies, research should be conducted into production processes, materials and part properties, with the results being fed back into the systems engineering process.
2) In order to make full use of the new design flexibility opportunities, systematic research should be carried out with a view to producing concrete design guidelines covering all the different Additive Manufacturing technologies.
3) Develop new data formats for Additive Manufacturing as soon as possible.
4) Analyse the ways in which Additive Manufacturing could potentially change and impact on value networks, the economy and society as a whole.

Implementation

5) Standardise the three data sets of digital 3D geometries, material formulae and process parameters.
6) Additive Manufacturing requires dedicated quality assurance methods and processes.
7) Accelerate the implementation of basic research in industrial applications.
8) Strategies are needed for integrating Additive Manufacturing with widespread conventional manufacturing systems.
9) Creation of decision-making tools capable of meeting future strategic planning challenges in connection with Additive Manufacturing.
10) Stimulate and support a dynamic start-up scene in order to leverage Additive Manufacturing's high potential for innovation.

Education

11) Augment traditional occupational profiles for skilled workers with new skills for Additive Manufacturing technologies.
12) Make use of Additive Manufacturing's potential for teaching STEM subjects in schools.

Funding

13) Establish a research programme geared towards implementation of the dual strategy of securing Germany's position as a leading Additive Manufacturing supplier and market.

2 Introduction

Additive Manufacturing refers to the production of parts by building up successive layers of a formless material in a vastly automated process based on digital 3D models. Rather than being one single technology, Additive Manufacturing is in fact a diverse technology field. In the public debate and the media headlines it is frequently referred to as 3D printing, a development that the media is all too keen to describe as a "revolution". However, the home 3D printers currently available on the market actually have very little in common with industrial Additive Manufacturing systems. One example of just how unrealistic the public's expectations can sometimes be was provided by an episode of German hidden camera show "Verstehen Sie Spaß", broadcast on 26 September 2015, in which unsuspecting members of the public were tricked into believing that people had been cloned using 3D printers. Since this statement concentrates on the technologies' industrial applications, it will hereafter be referred to as "Additive Manufacturing".

The basic ideas underlying Additive Manufacturing were patented in the 20th century – the patent applications for the first technologies were filed from the 1970s on, although at that point in time it was not yet possible to put them into practice. By the 1990s, advances in laser technology and ICT resulted in the first successful attempts at Rapid Prototyping, in which parts with limited functionality were produced as visualisation aids e.g. for product designers and surgeons. The big advantage of these prototypes is that they can be produced very quickly from a 3D data set. This reduction in lead time is possible because Rapid Prototyping eliminates the need for time-consuming process steps such as making moulds or assembling individual components. Nevertheless, in the early days, the manufacture of end products was still not economically viable, principally due to their unsatisfactory mechanical properties. However, the products' strength and durability were gradually improved, until Rapid Tooling – the manufacture of moulds and tools – eventually became feasible. After the turn of the millennium, it became possible to make finished products increasingly cost-effectively, particularly small parts, small batches and one-off items e.g. for the jewellery or medical and dental technology industries. This process was now referred to as Rapid or Direct Manufacturing. It opened up completely new design engineering possibilities such as the manufacture of geometrically complex parts from high-strength materials for use in lightweight construction. In 2010, the industry's leading companies agreed to replace the various application-specific, ambiguous and misleading terms prefaced by "rapid" with the new umbrella term "Additive Manufacturing". This is illustrated in Figure 1-1.

Additive Manufacturing technologies differ from conventional technologies in several respects. They have huge potentials if their specific characteristics are taken into account at every stage of product development and these are exploited systematically. As Additive Manufacturing technologies mature, their use increasingly broadens. The industry has been achieving annual growth rates in

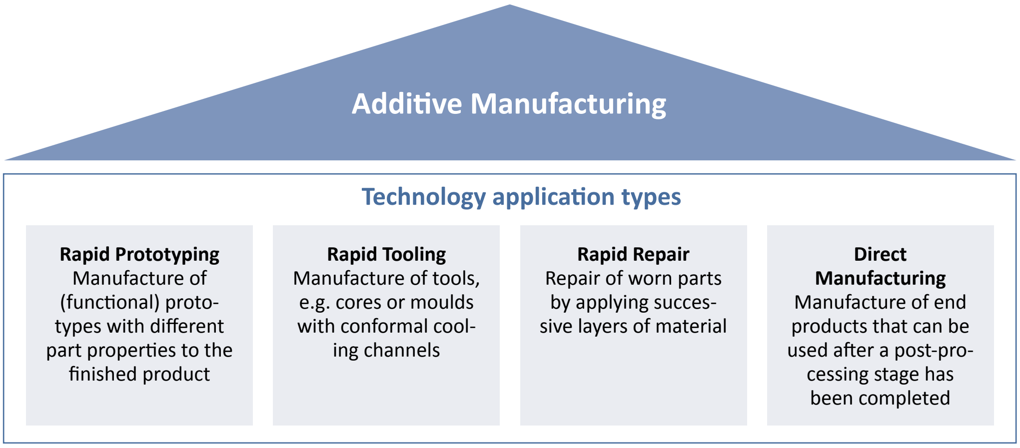


Figure 1-1: Terms in the context "Additive Manufacturing" (Source: [GK16], [LL16])

the region of 30 percent for some years now [Woh16]. There is good reason to believe that the technology field Additive Manufacturing will become established as a widespread manufacturing technology field existing alongside conventional production technologies in many different areas. However, there are currently no convincing signs to suggest that Additive Manufacturing will cause a revolution in industrial production any time soon – there is still a long way to go before it is possible to start talking in these terms. A second statement led by Leopoldina will address other areas of application (e.g. medicine, the construction industry and home 3D printing) where Additive Manufacturing could potentially have a revolutionary impact in the long run.

The characteristics of Additive Manufacturing that have been described above and its emerging potential benefits raise a number of **key questions** in connection with the overall conditions, the technologies, the value network and the impacts on society:

- Which opportunities and barriers exist with regard to the development and utilisation of this technology field?
- What is required to enable the use of Additive Manufacturing on an industrial scale for cost-effective high-volume production?
- How will it change value networks and business models?
- What needs to be done for Germany to achieve its goal of being a leading market and leading supplier?
- How will skills profiles change?

Objectives

The aim of this statement is to provide answers to questions such as the above and in particular to make recommendations about how to develop this technology field and make the most of its potential benefits. The paper is divided into four main chapters:

The first chapter on **"The Status Quo"** describes the current state of the technologies and the areas of application in which they are already being successfully deployed. It also looks at the actors in the value networks, current business models and success factors.

The second chapter on **"Anticipated Developments"** begins by considering probable future trends for the technologies and areas of application described in the previous chapter. It then goes on to outline potential developments in value networks and business models. Finally, it looks at future market trends and current funding initiatives.

The third main chapter **"Theses"** presents 21 conclusive statements about

Additive Manufacturing based on the two preceding chapters. Finally, the fourth main chapter contains a series of **"Recommendations"**.

Methodology

Figure 1-2 illustrates the methodology used to derive the recommendations. The project group drew a number of theses based on its analysis of the following five themes: manufacturing technologies, areas of application, value networks, business models and success factors. The status quo and anticipated developments were assessed for each theme. Recommendations were then formulated based on the analysis results and theses for the different themes. This methodology was complemented by two workshops attended by experts in the field of Additive Manufacturing.

Project Organisation

This paper is the first of two joint statement on Additive Manufacturing by acatech – National Academy of Science and Engineering, the German National Academy of Sciences Leopoldina and the Union of the German Academies of Sciences and Humanities. acatech acted as the lead institution for this statement, which focuses on technologies, value networks and business models.

The working group led by Leopoldina will begin by addressing the systemic challenges for basic research. It will then consider potential future Additive Manufacturing applications in fields such as medicine, food and construction. In addition, it will take an in-depth look at the interactions between Additive Manufacturing technologies and society, particularly in relation to the workplace, safety and home 3D printing (DIY). It will end with a discussion of the regulatory issues. The Leopoldina working group provided detailed feedback on the present statement and their suggested additions and references have been incorporated into it.

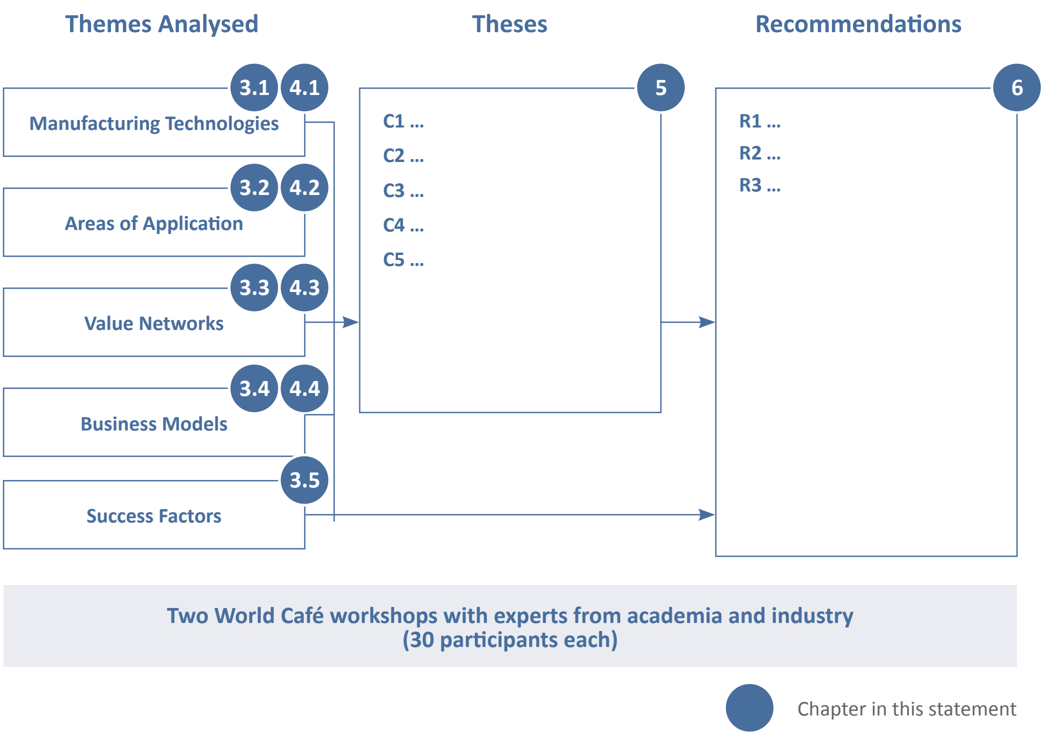


Figure 1-2: Methodology used to formulate recommendations (Source: authors' own illustration)

3 The Status Quo

Additive Manufacturing refers to the production of parts by building up successive layers of a formless material in a vastly automated process based on digital 3D models. This basic approach can be employed in conjunction with various different physical and chemical principles to achieve a solid bond. The joining techniques and process parameters, defined by the machines being used, determine which materials can be processed and which product properties can be achieved. Advances, particularly in laser technology, mean that increasingly high-performance materials can now be processed. In some instances, it is even possible to attain property profiles that are superior to those achievable using conventional production technologies.

In almost all established applications, Additive Manufacturing forms an integral part of an industrial value network. The Additive Manufacturing process itself is divided into three stages: 1) data preparation, 2) the layer-by-layer building of the object and 3) post-processing. At present, the data preparation and post-processing stages are not usually automated – they involve manual labour and largely rely on know-how acquired through practical experience. Examples of post-processing include the removal of support structures, heat treatment of metals and debinding and sintering of ceramic green compacts. Many of the items produced by Additive Manufacturing are not destined for use as a standalone end product or component. Instead, they are employed as fixtures, lost models (e.g. in lost-wax casting) or moulds. The ability to make a finished product in one single manufacturing step is likely to remain little more than a vision for some time to come.

This chapter describes the status quo of Additive Manufacturing. Since both the science and the technologies in this field are changing all the time, it is impossible to provide a completely up-to-date description of the status quo. Our aim here is to provide an overview of the Additive Manufacturing technologies and areas of application that are of most interest to industry. The second half of this chapter will focus on the actors in the value network and on business models.

3.1 Manufacturing Technologies

This section will describe the basic technological principles of Additive Manufacturing. It will begin with the data preparation stage which is fundamentally the same for all the different Additive Manufacturing technologies. It will then explain the principle of building an object layer-by-layer. Finally, it will take a look at the most important additive manufacturing technologies.

Data Preparation

As illustrated in Figure 3-1, the data preparation stage comprises a total of eight steps. The first step involves the creation of a computer-internal, native, relationally structured 3D CAD model. Geometries from 3D scanners[1] can also be used. In this reverse engineering process, the surfaces of a real object are initially

1 E.g. CT or structured-light scanners.

represented by point clouds derived from the relevant measurements. A mesh of triangles is then created from the points. Alternatively, higher-order curves – and thus parametric graphic elements – can be computed by the approximation of series of points [BER+12]. The .STL format (Standard Triangulation Language, Stereolithography or Surface Tessellation Language) has become established as the de facto standard for this process step. When 3D CAD data are used, the second step is to convert them to .STL format. However, the conversion process suffers from a number of serious problems. The .STL format only describes the surface geometry of the original three-dimensional object. This is approximated using a large number of triangles. Other information from the CAD system is lost, for example material data, curvature radii and dimensional tolerances.

The .STL format is particularly prone to inconsistencies. These generate additional work such as data analysis and repair, which slows down the entire process. The next step involves the orientation and positioning of the parts in the virtual build envelope. For Additive Manufacturing technologies that require the use of support structures, these are now designed in the position where they will be needed to support overhangs on the finished part. Depending on the Additive Manufacturing technology in question, the design of the support structures may either be automated or carried out manually, a task that requires a huge amount of process knowledge and practical know-how. In Selective Laser Melting™, for example, the way the support structures are designed is key to determining a part's manufacturability, the process stability and the amount of subsequent machining work required. The next step, known as slicing, involves generating horizontal slices of the 3D geometry. Because .STL files only describe the surface geometry in terms of triangles, the slices only contain the contours of the part being made. Consequently, the next step involves filling in

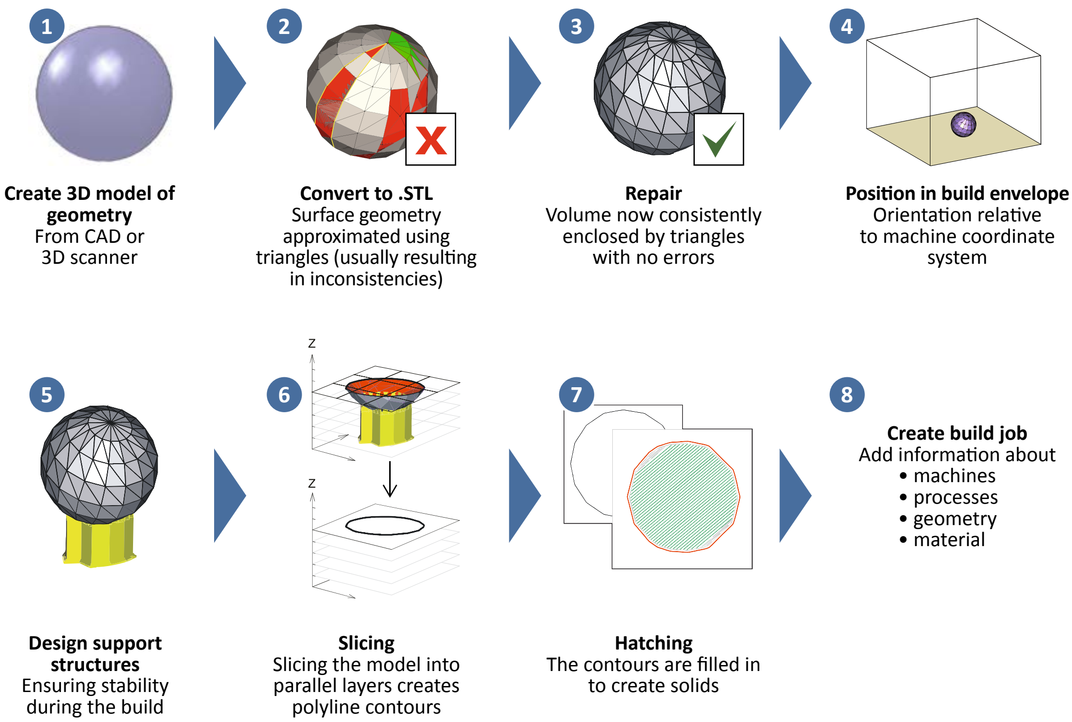


Figure 3-1: Data preparation process chain (Source: based on [Kar08])

the contours to create a solid. Although this step may be different in some Additive Manufacturing technologies (e.g. LOM™, see Figure 3-5), hatching is by far the most commonly used method for filling in the contours. Each individual hatching line will be laid down by the Additive Manufacturing machine later on in the process. Consequently, the hatching must take the machine, material and manufacturing process parameters into account. Before the actual process of building the part can begin, it is also necessary to define additional critical parameters specific to the part geometry, material, machine and process. This often has to be done manually.

Cyclical Layer Building

The physical Additive Manufacturing process involves cyclically repeated basic steps to produce a layer. How each layer is laid down in detail depends on the Additive Manufacturing technology in question. This is illustrated in Figure 3-2 using the example of Selective Laser Melting: a layer of metal powder is deposited and selectively fused with the underlying layer. The building platform is then lowered.

Geometric Freedom

The fact that objects are built up layer by layer eliminates the need for geometry-specific tools such as moulds which can often be time-consuming and expensive to make and store. The process is therefore also sometimes referred to as Direct Digital Manufacturing. Traditional part geometry constraints such as undercuts and draft angles no longer apply. Nevertheless, the actual degree of design flexibility and dimensional accuracy still depends on the limitations of the specific technology being used. Some technologies require support structures to prevent projecting layers and overhangs either from collapsing under the force of gravity or from warping due to residual stresses resulting from the build process. These structures must be accessible so that they can be removed once the build is complete.

Additive Manufacturing Technologies

Different Additive Manufacturing technologies employ different joining principles, from two-component adhesives to laser beam welding. Different joining principles enable additive processing of different materials such as thermosetting plastics and metals. The range of application areas and competing conventional manufacturing technologies for each Additive Manufacturing technology depend on which materials it is able to use. For instance, metals are more suitable than plastics for building parts that will be exposed to high temperatures in use. Whereas in conventional joining technologies prefabricated components are joined together via a seam, Additive Manufacturing builds up parts incrementally by joining the seams between a succession of layers, usually without any prefabricated elements. The main differences between

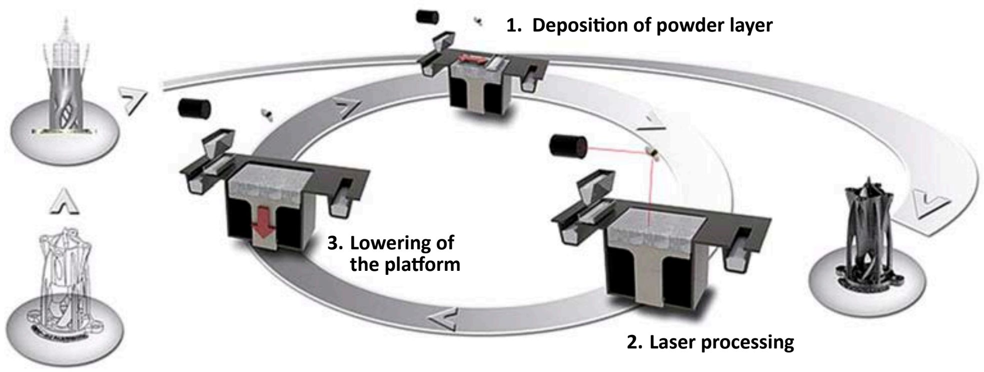


Figure 3-2: Illustration of cyclical layer building process using the example of selective laser melting (Source: [GWP13])

Additive Manufacturing methods and conventional joining techniques relate to the size of the seam and how long it takes to produce it. These factors also determine the detail resolution and productivity of a given Additive Manufacturing technology.

However, even if they use the same material and joining technique, Additive Manufacturing technologies can still be different from each other due to differing technical implementations of the feedstock delivery and layer contouring systems. The formless feedstock may come in the form of a powder, a wire, a liquid, or a foil or film. Different methods are also used to contour each individual layer, for example nozzles or blades travelling along a linear axis, the selective deflection of laser beams using moving mirrors, or electron beams guided by magnetic fields.

It is thus evident that the term "Additive Manufacturing" currently covers a broad spectrum of different technologies. There are major differences in the age and maturity of individual technologies [LSK03] and the same applies to current applications, potential future applications and the intensity and momentum of research and further development activities. Whether a particular technology is best suited to home use, simple workshops, specialised production laboratories or other target groups depends – among other things – on the size of the required investment. The cost of buying the equipment can be anywhere between 500 euros (Fused Deposition Modelling™) and over 1 million euros (Selective Laser Melting™). Moreover, the scale of the necessary safety measures and the knowledge required to operate the equipment safely (e.g. handling of flammable and respirable metal powders or laser safety) also vary depending on the technology.

Numerous different additive technologies now exist and this situation is further complicated by terminology that can at times be misleading. Virtually all additive equipment manufacturers – and even many users – are trying to establish their own trade names for processes that are in some cases identical. At the same time, the terminology used can often be rather ambiguous. Inevitably, international standardisation efforts are lagging behind the fast-moving reality on the ground. Moreover, they are not immune to lobbying and can sometimes even be contradictory. For instance, the DIN EN ISO 17296-2 standard that is currently still at the drafting stage defines a "Powder Bed Fusion" category that encompasses a range of technologies using either plastics or metal powders and electron beam or laser beam technology. These technologies are fundamentally different from each other, both in terms of their physics, chemistry, materials, processes and equipment and in terms of their industrial applications. In view of the fact that they are all becoming increasingly important, they will be treated separately in the remainder of this paper rather than being lumped together. The Association of German Engineers' VDI 3405 standard uses English terms to describe some of the processes by default. The acatech working group decided in favour of using the English terms and abbreviations which have the highest industrial prevalence at the moment, bearing in mind the technological differences. In the following technology overview the full English-language term and industry-standard abbreviation are being presented in first place, followed by important trade names, VDI 3405 process names and DIN EN ISO 17296 process categories under the "Synonyms" heading. Many processes and systems are protected by trademark, meaning that the relevant technologies and their future development are tied to individual companies. One example is Fused Layer Manufacturing, widely referred to as Fused Deposition Modelling™ (FDM™), which was patented by *Stratasys™* in 1989 and has now sold more systems for industrial applications than any other Additive Manufacturing technology. When the basic patent for this technology expired in 2009, a raft of simpler and much cheaper non-proprietary products came onto the market, making FDM™ accessible not only to researchers but also to hobbyists. The massive proliferation of FDM™ that occurred as a result has been largely responsible for the current surge in interest in Additive Manufacturing as a whole.

The next section provides an overview of the most commercially important Additive Manufacturing technologies and their different joining principles, layer contouring methods and materials.

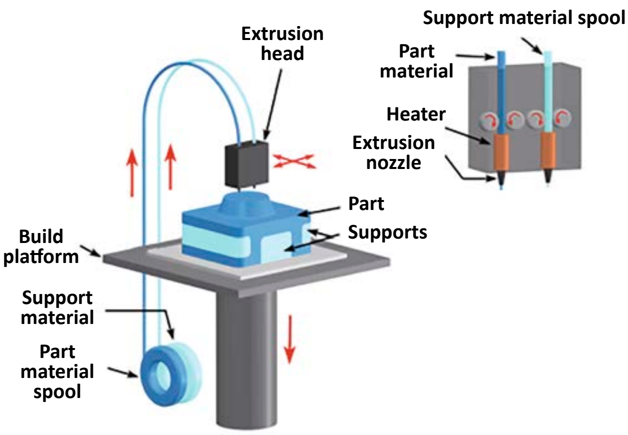


Figure 3-3: Fused Deposition Modelling (FDM™) (Source: CustomPartNet LLC)

Fused Deposition Modelling™ (FDM™)

Synonyms: Fused Layer Manufacturing/Modelling (FLM)
Category: Material extrusion
Market launch: 1991
Patented: 1989 Scott Crump
Joining principle: Hot melt adhesive bonding
Layer contouring: Extrusion e.g. of plastic filaments from a moving nozzle
Materials: Plastic filaments, e.g. amorphous thermoplastics (ABS[2], PC[3], PLA[4], PI[5])
Special features: More systems sold than any other technique.

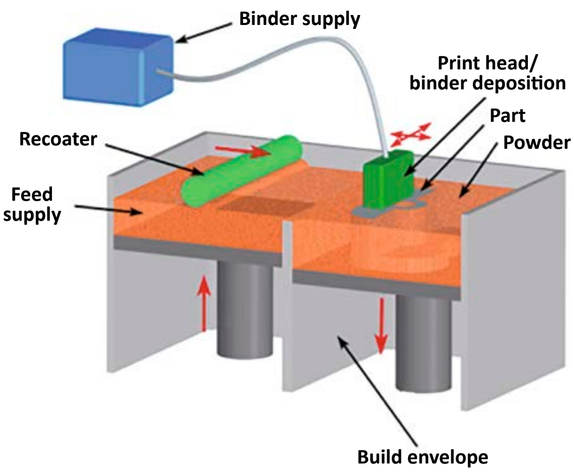


Figure 3-4: 3D Printing (3DP) (Source: CustomPartNet LLC)

3D Printing (3DP)

Synonyms: Binder 3D printing, ZCorp™, VoxelJet™
Category: Binder jetting
Market launch: 1993
Patented: 1993 Massachusetts Institute of Technology
Joining principle: Powder particles bonded with liquid binder
Layer contouring: Binder selectively deposited by ink-jet printhead
Materials: Gypsum, starch, PMMA[6], sand
Special features: The binder can be dyed and mixed via multiple nozzles, making it possible to print multi-coloured objects. If ceramic powders are used, green compacts can be built and then sintered in subsequent process steps. Does not require support structures.

2 ABS: Acrylonitrile-Butadiene-Styrene.
3 PC: Polycarbonate.
4 PLA: Polylactic acid.
5 PI: Polyimide.
6 PMMA: Poly(methyl methacrylate).

Laminated Object Manufacturing (LOM™)

Synonyms: Laminated Object Modelling™ (LOM™), Layer Laminated Manufacturing (LLM), Sheet Lamination
Category: Layer lamination
Market launch: 1991
Patented: 1987 Michael Feygin
Joining principle: Gluing together of layers of paper or hot melt adhesive bonding of PVC[7] sheets
Layer contouring: Cut to shape with a knife (or laser cutter, which is now obsolete)
Materials: Paper, adhesive, PVC sheets
Special features: The paper can be printed in advance, allowing coloured objects to be produced that possess wood-like properties. Does not require support structures.

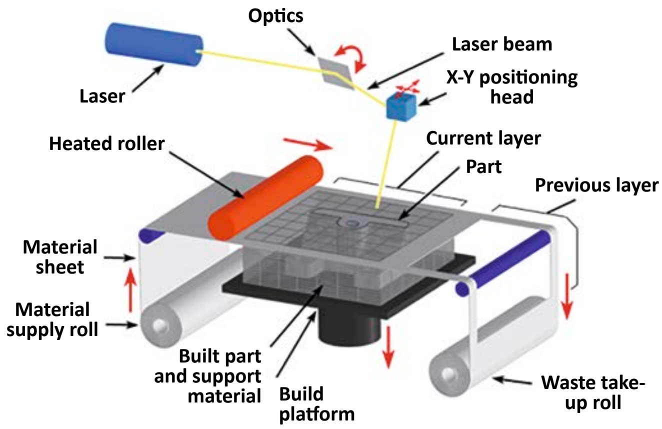


Figure 3-5: Laminated Object Manufacturing (LOM™) (Source: CustomPartNet LLC)

Stereolithography (SLA™)

Synonyms: STL
Category: Vat polymerisation; photopolymerisation in a vat using a laser light source or controlled surface lights
Market launch: 1987
Patented: 1984 Charles Hull
Joining principle: Photopolymerisation
Layer contouring: Selective exposure to focused laser beam directed by scanning mirrors or incoherent light directed by micromirror arrays (DLP™, similar to video projector)
Materials: Thermosetting plastics, typically acrylic and epoxy resins
Special features: Resins mixed with ceramic powder allow green compacts to be produced that can be sintered after further process steps have been completed.

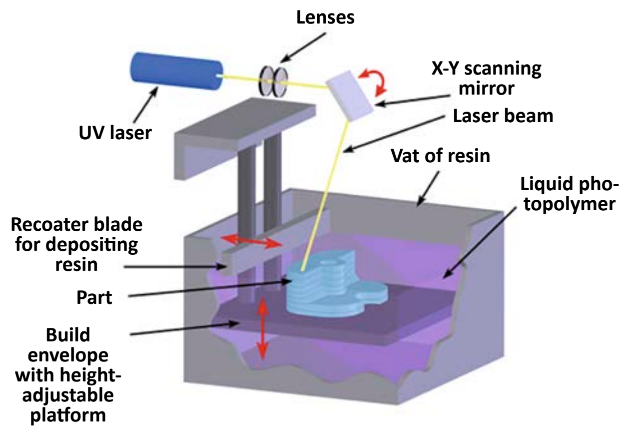


Figure 3-6: Stereolithography (SLA™) (Source: CustomPartNet LLC)

Polyjet™ Modelling (PJM™)

Synonyms: Objet™
Category: Material jetting
Market launch: 2000
Joining principle: Photopolymerisation
Layer contouring: Selective deposition of photopolymers using ink-jet printhead
Materials: Thermosetting plastics, typically acrylic and epoxy resins
Special features: Single droplets of different thermosetting plastics can be combined to create custom colour blends, as well as hard and rubber-like areas within a single part.

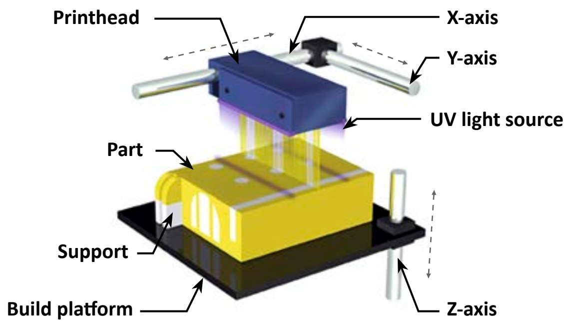


Figure 3-7: Polyjet™ Modelling (PJM™) (Source: Stratasys)

7 PVC: Polyvinyl chloride.

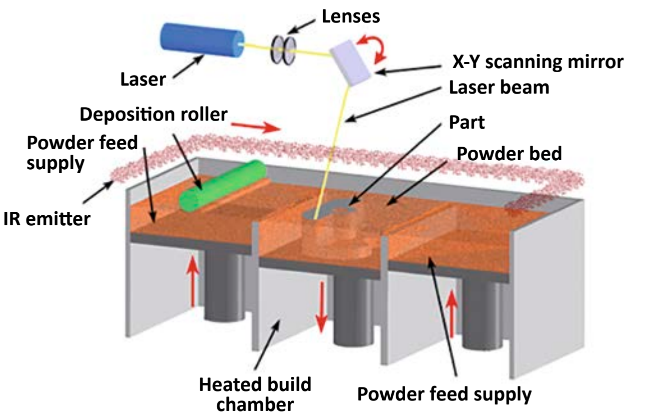


Figure 3-8: Selective Laser Sintering™ (SLS™) (Source: CustomPartNet LLC)

Selective Laser Sintering™ (SLS™)

Synonyms: Polymer Laser Sintering
Category: Powder bed fusion
Market launch: 1992
Patented: 1986 Carl Deckard
Joining principle: Liquid phase sintering
Layer contouring: Selective exposure to focused CO_2 laser beam directed by scanning mirrors
Materials: Semicrystalline thermoplastics, typically PA[8] 12, PA 11, PAEK[9]
Special features: Does not require support structures.

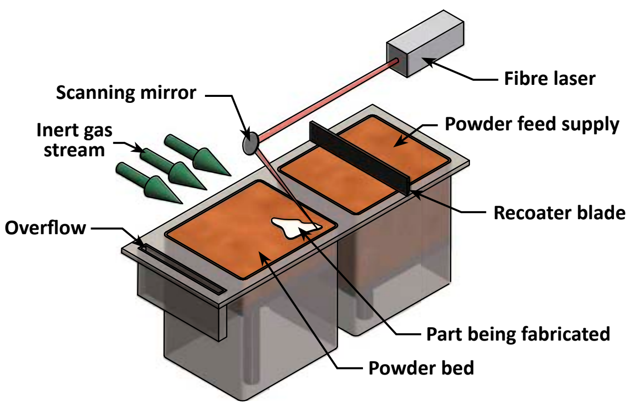


Figure 3-9: Selective Laser Melting™ (SLM™) (Source: RAS)

Selective Laser Melting™ (SLM™)

Synonyms: Direct Metal Laser Sintering™ (DMLS™), LaserCUSING™, Laser Metal Fusion™ (LMF™), Direct Metal Printing™ (DMP™), Laser Beam Melting (LBM), Direct Metal Laser Melting
Category: Powder bed fusion
Market launch: 1999
Patented: 1996 Wilhelm Meiners
Joining principle: Fusion welding
Layer contouring: Selective welding using focused solid-state laser beam directed by mirrors
Materials: Weldable metals and powdered metal alloys
Special features: Material properties as in conventional processing.

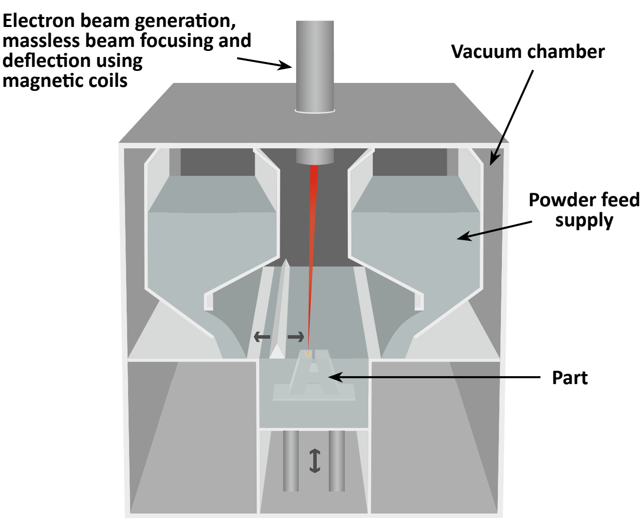


Figure 3-10: Electron Beam Melting™ (EBM™) (Source: Arcam)

Electron Beam Melting™ (EBM™)

Category: Powder bed fusion
Market launch: 2004
Joining principle: Fusion welding
Layer contouring: Selective welding using focused electron beam directed by magnetic fields
Materials: Sinterable and weldable metals and powdered metal alloys
Special features: Material properties as in conventional processing. The surrounding powder bed must be lightly sintered in order to dissipate the electrical charge in a controlled manner. This makes it harder to remove the powder from cavities than in SLM™, resulting in rougher surfaces.

8 Polyamide.
9 Polyaryletherketone.

Laser Metal Deposition (LMD)

Synonyms: Direct Metal Deposition (DMD™), Laser Engineered Net Shaping (LENS™), Electron Beam Additive Manufacturing (EBAM™),
Category: Directed energy deposition
Market launch: 1997
Joining principle: Fusion welding using laser or electron beam
Layer contouring: Optics and nozzle or wire feed guided by linear axis or articulated arm robots
Materials: Weldable metals and metal alloys, reinforcing ceramic particles
Special features: Welding either of metal powder that is transported into the melt pool by a stream of gas, or of metal wire guided by laser or electron beams; freeform fabrication possible; material composition can be easily varied for each layer.

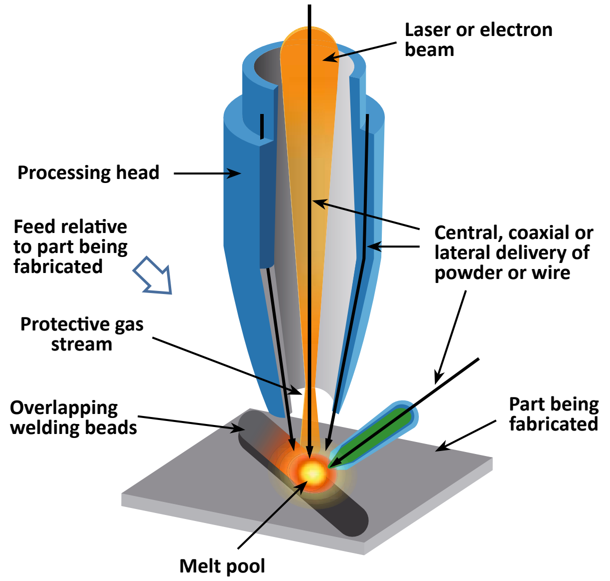


Figure 3-11: Laser Metal Deposition for Additive Manufacturing using powder or wire (Source: authors' own illustration)

3.2 Current Areas of Application

This section will provide an overview of Additive Manufacturing's current areas of application in the context of industrial manufacturing. The main areas include prototyping, the fabrication of models and moulds, aids such as fixtures, templates and drilling jigs and, last but not least, the manufacture of end products. The burgeoning use of Additive Manufacturing technologies in other areas of application such as medicine, art and home 3D printing will not be addressed here.

Prototyping

Prototyping was one of the first areas to use Additive Manufacturing and it has now become indispensable in this field. The extremely short lead times of Additive Manufacturing are a critical benefit in prototyping, while the higher costs are an acceptable trade-off.

A distinction can be drawn between the following types of prototypes, depending on their intended use:

- concept or visualisation models with a purely aesthetic function (3DP, LOM™, SLA™, PJM™, FDM™),
- geometric prototypes, e.g. for fitting simulations (FDM™, PJM™, SLA™, SLS™),
- function prototypes that must perform defined individual functions of the eventual product (SLS™, FDM™, SLM™),
- "technical prototypes" that only differ from the finished part in the way they are made, but are identical in terms of the materials used and their geometry and functionality (SLM™, EBM™).

Fabrication of Models and Moulds

Additive Manufacturing technologies themselves have no need of models and moulds because they build parts directly from 3D data. They are, however, widely used in the production of models and moulds. In many instances, the only alternative would be to make these items by hand, as in the case of moulds for lost-wax precision casting (PJM™, SLA™) or positive models used in the production of sand moulds and silicone moulds (see Figure

3-12). 3DP makes it possible to produce sand moulds of several metres in size for metal casting with more complex geometries than are possible using conventional manufacturing technologies.

Figure 3-12: Silicone mould for a mobile phone housing made by SLA™ (Source: rpprototype.com)

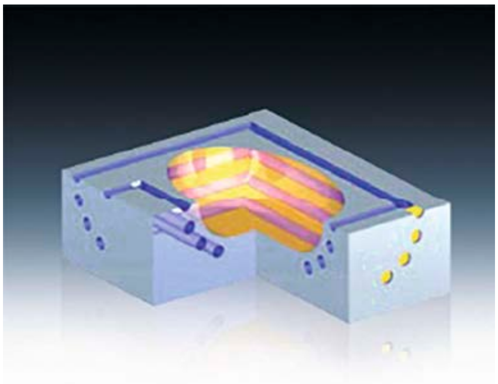
Steel mould inserts for high-volume thermoplastic injection moulding or light alloy die casting are also produced by Additive Manufacturing (SLM™). As illustrated in Figure 3-13, cooling channels with water flowing through them are positioned in the mould insert in such a way as to keep the temperature as uniform as possible during use (so called conformal cooling). SLM™ allows the cooling channel shape to be optimised so that it follows the profile of the mould core, providing enhanced performance compared to conventional cooling channel drilling which can only produce cooling channels in a perfectly straight line, for example. The end result is that additively manufactured mould inserts provide better dimensional accuracy in the injection-moulded parts, as well as reducing cycle times and thus delivering significant cost savings for typical injection moulding batch sizes of several hundred thousand.

Fixtures, Templates and Drilling Jigs

Additive Manufacturing has also been used for several years to produce manufacturing and surgical aids. Patients' individual anatomy can be captured digitally using modern imaging techniques, making it possible to produce anatomically-shaped medical products. Dental implants, for example, can be designed using CT scan data. A drilling jig is then made by SLA™ in order to guide the drill so that it precisely follows the 3D design. This helps the operator to work quickly and accurately. Similar drilling jigs made by SLS™ are used in clinical practice for knee operations.

Manufacture of End Products

The SLA technology made by *Envisiontec™* has at present almost completely cornered the market for individual, made-to-measure in-the-ear hearing aids and high-end hearing protection devices. A comparatively lower but nonetheless steadily growing market penetration has been achieved by SLM™ in the production of cobalt-chromium or gold alloy dental crown frameworks (Figure 3-14) to which a ceramic veneer is subsequently added. The second statement will take a closer look at other Additive Manufacturing applications in the field of medical tech-



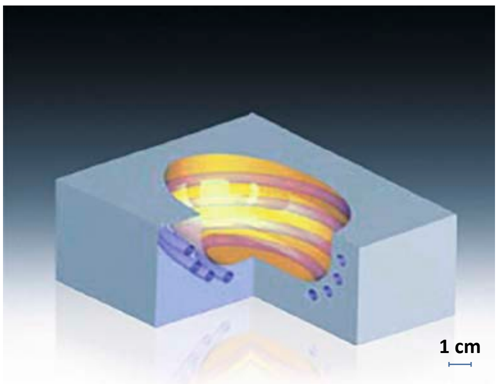


Figure 3-13: Left: conventionally drilled cooling channels; Right: conformal cooling channels produced by SLM™ [Source: EOS]

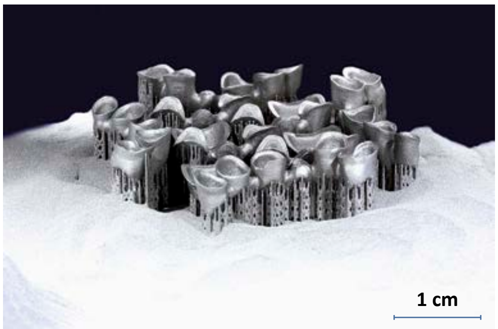


Figure 3-14: Cobalt-chromium denture frameworks on support structures, made by SLM™ (Source: www.trident.ee)

Figure 3-15: Water pump wheel for the motorsport industry, made by SLM™ (Source: BMWgroup.com)

Figure 3-16: Fuel nozzle for LEAP engine, made by SLM™ (Source: General Electric)

nology. Figures 3-15 and 3-16 show examples from the motorsport industry (*BMW* water pump wheel) and aviation industry (*General Electric* fuel nozzle). As well as meeting the high manufacturing reliability and reproducibility standards that are part and parcel of the aviation industry, the *GE* part is particularly noteworthy because of the comparatively high production volumes for Additive Manufacturing: more than 100,000 of these fuel nozzles have already been pre-ordered for the LEAP engine. In the previous engine design, the fuel nozzle was assembled from 18 individual elements. SLM™ allows it to be made as a single part with a more complex shape, saving weight and reducing production costs.

3.3 Roles in the Value Network

Diverse value networks have formed around Additive Manufacturing, in which specific roles are typically assumed by different actors.

Material Manufacturers: Material manufacturers produce the feedstock for Additive Manufacturing, for example metal or plastic powder, plastic filaments, photo-resins, binders, etc. They include both established chemical industry players (e.g. *Evonik Industries*) and small specialist firms (e.g. *TLS Technik*). New and demanding business areas are emerging, especially with regard to the metallurgical development of alloys that meet the high purity standards for the metal powders used in Additive Manufacturing – e.g. titanium and nickel alloys.

Component Manufacturers: These are the companies that supply components and modules for making Additive Manufacturing equipment. Particularly process-critical components include lasers, control technology, coaters, mirrors, laser/electron beam control components and build chamber heating systems. Laser manufacturer *IPG Photonics* is one example of a component manufacturer.

Test Equipment Manufacturers: Additive Manufacturing is heavily reliant on non-destructive testing – uncertainty about the reliability of this new technology means that 100-percent testing is often required. Non-destructive testing of parts is in any case indispensable when producing batch sizes of 1. Additionally, test equipment (e.g. imaging technology) is already used during the build process in order to continuously counteract errors.

Machine Manufacturers: These are the producers of the machines used for the layer-by-layer manufacturing of parts. Most machine manufacturers specialise in one or at most a couple of manufacturing technologies. Alongside the market leaders, whose focus is primarily on traditional metal and plastic technologies (e.g. *3D Systems, Stratasys, EOS*), a number of smaller companies are currently establishing themselves in niche technologies (e.g. *Lithoz, Carbon3D*).

Data Preparation Software Providers: These companies supply the software that makes it possible to combine geometric, process and material data (see Chapter 4-1). Belgian company *materialise* is the market leader for industrial applications.

Online Shop Operators: Several companies are attempting to apply e-commerce business models to Additive Manufacturing by providing an interface between the manufacturing service and the end customer. The key value proposition to the end customer includes the ability to customise consumer goods (high number of product variants) and supply products that cannot be obtained anywhere else. In most cases, the companies using these business models have their own manufacturing capability but do not carry out their own development – instead, they use a crowdsourcing model where development work is undertaken by independent designers. The best-known example of this model is the Dutch-American firm *Shapeways*.

Service Providers: These companies mainly build to order using additive technologies; many possess an extensive technology portfolio. They also often offer engineering and prototyping services. They are key drivers of the technologies, since many companies are reluctant to run the risk of investing in their own in-house production facilities. Examples of service providers include *materialise*, *FKM* and *citim*. Moreover, individual service providers are increasingly positioning themselves as platforms providing access to processes and data via digital interfaces (APIs), thereby acting as enablers of other actors' business models.

Brokers: As the number of manufacturing service providers continues to grow, players have appeared on the scene who act as brokers between the end customer and the manufacturing service provider. Their services are predicated on the demand for "spot markets" for trading standard (manufacturing) services. Current examples of brokers include *Kraftwürx*, *3D Hubs* and *Additively*.

Technology Users: These are the industrial enterprises and home users who use additive technology to make parts for their own use or buy them in from service providers.

There are also a number of key industry enablers that support the Additive Manufacturing industry value network.

Research Institutes, Universities and other higher education institutions: These organisations conduct interdisciplinary research in the field of Additive Manufacturing. They perform an important catalyst role through application-oriented projects in partnership with industry. They carry out applied and empirical research for the entire value network. In so doing, they drive the technology's development and accelerate its uptake. Examples include *DMRC, SFB 814, Fraunhofer Additive Manufacturing Alliance, the Rapid Technologies Center* in Duisburg and several laser centres. They also train staff to use the technologies.

Standardisation Committees: As part of the continuing efforts to enable the use of Additive Manufacturing

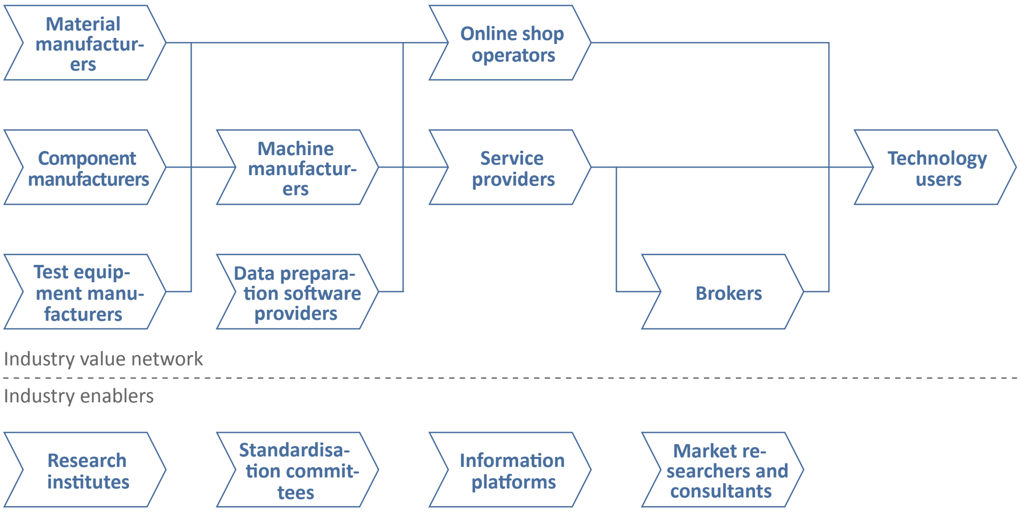


Figure 3-17: Generic Additive Manufacturing value network incl. enablers (Source: based on [BBM+14] and [Thi14])

in highly demanding industrial applications, work is ongoing to further standardise the different techniques. The most important international committees are ASTM Committee F42, ISO TC 261 and CEN TC 439. The key actor in Germany is VDI technical committee 105 Additive Manufacturing.

Information Platforms: Trade fairs and conferences that provide an opportunity to share knowledge (e.g. AMUG, *formnext, inside3dprinting, Rapid.Tech* in Erfurt, *Solid Freeform Fabrication Symposium*).

Market Researchers and Consultants: Suppliers of reliable information about the technology and advice on rolling it out. These organisations typically possess extremely in-depth industry- and technology-specific expertise (e.g. *Wohlers Associates, T.A. Grimm & Associates*).

3.4 Business Models

At a theoretical level, it is frequently suggested that Additive Manufacturing will lead to disruptive business model innovations. In practice, however, there have so far only been occasional hints that this might be happening in certain cases. The industry remains predominantly traditional in nature – the key actors are material and machine manufacturers, manufacturing service providers, test equipment manufacturers and technology users. The business models of these actors are little different to those found in traditional manufacturing industry. The material manufacturers still produce materials and sell them to their customers either directly or via distributors. Software continues to be licensed, test equipment manufacturers make and sell test equipment, and so on. All that the actors have done is add new products, services and know-how to their established business models. Material manufacturers, for example, have had to develop expertise in metal powder atomisation. But this has made little difference to their business models. Based on current practice, the following three conclusions can be drawn about Additive Manufacturing's impact on business models:

Use of Established Business Model Patterns

One specific feature that has emerged in the Additive Manufacturing industry compared to conventional manufacturing is that machine manufacturers have added materials and process parameters to the products that they market. Many suppliers use the consumer goods industry's well-known “razor and blades”[10] business model in which customers can only buy complementary products like materials and process parameters from the supplier of the original product. The high prices charged for materials and process parameters generate high margins and are responsible for a significant percentage of these companies’ turnover. The orchestrator model employed by *additively* is an example of a different type of business model in which instead of using Additive Manufacturing to make parts itself, the company acts purely as a production capacity broker. It is clear that **established business model patterns** play an important role in the Additive Manufacturing industry. This observation is in line with Gassmann et al.’s finding that 90 percent of all business models can be assigned to just a handful of basic patterns [GFC13].

New Key Activities and Partners

Additive Manufacturing business models often call for a company to modify its **key activities** or **key partners**. For instance, service providers often have to provide their customers with advice about the part design. This is due to the new level of design freedom, the lack of standards, and the fact that customers do not know enough about the limitations of different techniques and the optimal design principles for additively made parts. To address these challenges, they either need to bring in external key partners or build up in-depth process know-how themselves. Service providers are thus key actors in Additive Manufacturing value networks. Rather than interchangeable suppliers, they are in fact important enablers of the technologies’ growth in the industrial sector.

Business Models with an Individual Value Proposition

There is nothing fundamentally new about companies providing digital services to make individual parts for customers. *eMachineShop* was founded as long ago as 2003, for example. Its customers receive easy-to-use CAD software which they use to generate their own CAD data. The data is then sent to *eMachineShop* who make the parts with their own machinery and deliver them to the customer. Similar services quickly became established in the Additive Manufacturing sector (e.g. *Shapeways*, *i.materialise*, etc.). What sets them apart, however, is that they enable a very direct **form of customer interaction** combined with a **high level of design flexibility**. Customers can choose from an existing portfolio of CAD data that can then be customised. *trinckle 3D*, for example, provides a cloud-based marketplace that allows CAD data suppliers to precisely specify how much freedom customers have to customise parts (e.g. modify their dimensions). In conjunction with intuitive 3D CAD web applications, this allows the production of customised products down to a batch size of 1, ensuring that the customer’s requirements are met as closely as possible. Another recent development is the emergence of digital interfaces which rather than being designed for end users are aimed at companies with business models based on automated production outsourcing. One example is the *materialise API* made by the company of the same name. This interface provides white label functionality, allowing Materialise’s manufacturing service to be integrated into third-party business models without being visible to the customer.

3.5 Success Factors

For the purposes of this statement, a group of academics and company representatives evaluated **14 success factors** that play a key role in the technology field of Additive Manufacturing. They assessed both the importance of each success factor for industrial applications (*y*-axis) and Germany’s current position in the area in

10 Also known as “lock-in” or “bait and hook”. See Nespresso, Gillette and HP [GFC13].

question (*x*-axis).[11] The results are depicted in Figure 3-18, which divides the success factors into three broad groups:

- **Critical Success Factors:** These are factors that are very important but where Germany's current position is either weak or not strong enough. In total, there were nine such factors where further action is required. One especially important factor is the availability of robust machinery with reproducible output. Additive Manufacturing machinery and equipment currently fails to meet this requirement. There is often variation in the properties or geometry of the fabricated parts, even though the same data was used to produce them. The survey also identified machine productivity and process chain automation as areas with need for improvement. Moreover, if Additive Manufacturing is to be used more widely in industrial applications, it will be necessary to guarantee the availability of the appropriate materials. A need for further action was also identified with regard to the formulation of specific design and engineering guidelines for the different additive techniques (see also [TDD+15]). Further factors required for the technologies to be used more widely on an industrial scale include automated process chains and ways of integrating Additive Manufacturing with existing manufacturing processes. Norms and standards are also critical to the success of Additive Manufacturing. Standards are currently being developed by

Figure 3-18: Success factors for the Additive Manufacturing technology field (Source: authors' own illustration)

11 Survey conducted between 18 and 29 January 2016. 84 participants from academia and industry. The success factors were identified during a project group workshop [Wor14b].

bodies such as the Association of German Engineers (*VDI*) and the international standardisation organisation *ASTM International*[12]. In addition, there is a need to develop quality assurance methods capable of proving that additively manufactured parts can meet the relevant performance standards. Finally, even today there is already a shortage of the qualified personnel needed to carry out Additive Manufacturing work.

- **Balanced Success Factors:** These are the factors where there is a balance between their importance and the current position of the industry in Germany. The five factors in this category are: the existence of a research roadmap, legal clarity regarding product liability, data security, the existence of enablers for rolling out Additive Manufacturing and Germany's position with regard to basic research. Factors such as legal clarity regarding product liability and data security in digital process chains will become more critical to success once manufacturing technologies become faster and more reliable and once Additive Manufacturing becomes more widespread in industrial applications and the range of additively manufactured products increases. Basic research is one of Germany's main strengths and action should be taken to ensure that this continues to be the case in the future. At present, there are also sufficient enablers of Additive Manufacturing, primarily service providers, research institutes and business consultants with expertise in this field.

- **Overrated Success Factors**: These would be factors where Germany is strong but that are not so important to success. It is typical of a new technology that there should initially be no factors in this category.

Overall, there were no significant differences in the assessments made by the representatives from academia and industry.

12 For other (international) standardisation committees, see [VDI14].

4 Anticipated Developments

Additive Manufacturing is continually maturing and the industry has been achieving growth rates in the region of 30 percent for some years now [Woh16]. There is good reason to believe that Additive Manufacturing will become established as widespread manufacturing technologies existing alongside conventional production methods in many different areas. However, there are currently no convincing signs to suggest that Additive Manufacturing will cause a revolution in industrial production. This chapter looks at how the technology is expected to develop up to 2025. Its predictions are based on an analysis of the relevant literature, together with workshops, expert surveys and papers produced by the project group members in which, for example, they formulated future scenarios for the anticipated development of the technology, markets and business models [GEK+11], [GEK+12], [GEW13].

4.1 Manufacturing Technologies

The interplay of technology push and market pull has already resulted in a broad spectrum of application areas and this trend looks set to continue. This section will consider the anticipated technological developments up to 2025. There are two distinct development directions for manufacturing technology innovations. First of all, existing systems and technologies are going to be improved right up to their physical limits. Secondly, intensive research in the field of machine development is likely going to result in entirely new technologies by 2025, opening up new areas of application [TSE+15]. These developments are being driven both by research (funded by the government and other actors) and by the market pull from industry [GE13]. Other important advances in manufacturing technology will result from automation, the development of hybrid manufacturing systems, a wider range of materials and the ongoing development of Additive Manufacturing software.

Machine Productivity Improvements in the known Dimensions

The performance of Additive Manufacturing machinery is expected to improve significantly over the coming decades [PWC13], [RAE13]. An in-depth analysis of the technical parameters lies outside the scope of this statement. Different sources predict that build rates will increase by somewhere between a factor of 4 and a factor of 100 over the next ten years, especially in metal-based Additive Manufacturing [GEW13], [Sie14], [KTH+12]. Similar productivity gains of several orders of magnitude are not anticipated for conventional manufacturing technologies. However, it is unlikely that performance improvements on this scale will be achieved without further basic research and new actors entering the market. The current growth in the market means that additive machinery manufacturers, most of which are SMEs, are already working at full capacity. Against this background, improvements in machine performance are not occurring fast enough. In addition to addressing the complex technological issues, machine manufacturers will also need to put a lot of effort into scaling up their business models.

In the future, machine manufacturers will continue to differentiate themselves on the basis of faster build times, higher quality and larger build volumes. One of the main selling points of the latest generation of machines made by German machine manufacturers *ConceptLaser* is the 27 percent increase in build volume. This is intended to consolidate the company's market position as a supplier of metal processing machines with large build volumes [CL16a-ol]. Thanks to strong government support, an SLM™ machine is currently being developed in South Africa with a build chamber measuring 2000 mm x 600 mm x 600 mm [Wat15-ol]. This represents roughly a 20-fold increase compared to current models.

Technology users also sometimes complain about the machines' low availability due to the need for unscheduled maintenance work and the generally short maintenance intervals, e.g. between filter changes. Machine manufacturers can be expected to respond by taking steps to increase machine availability e.g. by making bigger filters [CL16b-ol]. Moreover, the latest generations of metal laser melting machines are already equipped with multiple lasers and will soon be further enhanced with automatic transport systems [SLM15-ol].

In the future, Additive Manufacturing machinery and equipment will be available as self-contained, encapsulated systems – the handling of both the powder and the part will be fully automated so that users do not come into contact with the powder [EOS16-ol]. Online monitoring functionality will also increasingly be added to existing machines [Wor14b], [AI15-ol]. This will mean that it is even possible to test a part's quality during the build process. Another key technological development will involve the automation of Additive Manufacturing machinery and equipment. At present, many of the steps in the Additive Manufacturing process have to be carried out manually. This applies both to the main build stage and the pre-build and post-build operations. The automation of Additive Manufacturing machinery and equipment will be accompanied by an exponential increase in the volume of process and part data that needs to be processed. Consequently, over the medium term machine manufacturers will have to add big data solutions to their portfolios in order to meet the market's demand for stable and reproducible processes.

Growing Technology Portfolio

One characteristic feature of the development of Additive Manufacturing is that the different additive technologies are largely aimed at different areas of application. This means that at present companies very rarely have the luxury of choosing between different technologies because the pros and cons of each one are so specific. This situation is unlikely to change any time soon [Wor14b]. Nevertheless, from time to time new layer-wise production technologies emerge. These new technologies can expand the range of potential applications. One example is the recently launched CLIP technology that is able to achieve significantly faster build speeds by enhancing the established DLP™ photopolymerisation method with a window that allows oxygen and light to pass through it, as well as employing specially adapted materials [TSE+15]. Another characteristic shared by many additively manufactured parts is that the material properties are anisotropic. In other words, properties such as strength are highly dependent on the direction of the forces acting on the part. This characteristic is a consequence of the orientation of the part in the build chamber while it is being built [NLR+13]. It can be used to good advantage, e.g. for parts that will principally be subject to forces acting in a limited number of main directions. However, it will be necessary to develop software that allows these properties to be incorporated into the part's design.

Hybrid Manufacturing Machinery and Equipment

Additive Manufacturing is particularly good at producing complex shapes. However, additive technology is as yet unable to match the productivity of conventional manufacturing processes. Established technologies such as turning and milling can deliver high precision and a high-quality surface finish with comparatively short processing times [MAV14-ol], [DMG15-ol]. Machine manufacturers are responding by augmenting additive and conventional manufacturing technologies. The results are referred to as hybrid manufacturing machinery and equipment. Although these machines can deliver high precision and a high-quality surface finish, they do sacrifice a degree of design freedom as far as the part's geometry is concerned. Two main categories of hybrid manufacturing machines become apparent:

Single build chamber: With these machines, parts can be built in a single, closed build chamber. One of the key features that sets this type of machine apart is that they allow post-processing operations to be performed in places that are no longer accessible on the finished part. In other words, conventional processing operations can be carried out after each layer has been deposited. Suppliers of these machines include *DMG Mori* and *Matsuura*.

Multiple build chambers: In this instance, Additive Manufacturing machines are integrated into an automated system. This allows process steps before and after the Additive Manufacturing stage to be configured as required. The parts are processed in different build chambers/workspaces [AI15-ol]. This addresses one of the main drawbacks of hybrid manufacturing machines that only have a single build chamber: the significant difference between additive and conventional manufacturing processing times, which can result in lengthy downtime e.g. for milling heads. Modularisation of the individual processing steps is a key success factor for this type of system. *Additive Industries* is one supplier hoping to provide such systems in the future.

Increasing Range of Materials

Dedicated materials are being developed to meet the requirements of new areas of application such as the automotive industry [Str15-ol], [WHW+15], [Yad09]. The fact that Additive Manufacturing is increasingly being employed to make end product means that the powder, filaments and resins, etc. have to meet more stringent requirements. High-performance materials already exist for individual areas of application such as the aviation industry. However, there are still problems with high-performance materials that are difficult to weld, for example. New materials or techniques will need to be developed in order to enable the use of Additive Manufacturing for high-temperature applications.

In the future, combinations of similar materials (e.g. two metals) or different materials (e.g. plastics and glass-fibre reinforced plastics) will be trialled and implemented. These combinations of materials will make it possible to achieve new properties for the additively manufactured parts. Customised materials are also being developed that can produce desirable part properties in conjunction with standardised process parameters [Wor14b]. Research is currently being carried out into the processing of titanium aluminides [SK14], shape memory materials [HMF12] and metallic glasses [KAH+15]. There are potential advantages to using these materials in Additive Manufacturing, since conventional manufacturing techniques can only produce a limited range of shapes with them and the processing costs are also typically very high.

A further example was provided towards the end of 2014 by researchers at the *Massachusetts Institute of Technology* who developed “programmable materials” (metamaterials, also known as architectured materials) exclusively for use in Additive Manufacturing. These materials can alter their own geometry in response to light, sound or electrical impulses [Thi15-ol].

Spread of Technology-specific CAD

Additive Manufacturing data preparation is currently still a complex process involving multiple stages (see Chapters 3.1 and 3.3). In the future, it is anticipated that CAD software will become available that takes the technologies’ specific constraints into account directly when creating the 3D model. In other words, Additive Manufacturing data preparation will be partially integrated into future CAD software. The first moves in this direction are already occurring today. For instance, CAD software company *Autodesk* acquired the AM software firm *netfabb* in 2015 in order to support the ongoing development of its own Additive Manufacturing CAD software. This suggests that the Additive Manufacturing market is now big enough to interest some of the larger players. As well as the actual CAD application, it is anticipated that the need for new simulation tools and management software system interfaces will also be met. This is confirmed by current developments in the field of Additive Manufacturing simulation tools. *Altair Engineering*, for example, is already selling software for optimising the design and analysis of parts being made by Additive Manufacturing. In the future, CAD software companies will also implement this targeted Additive Manufacturing functionality in their software. It will provide users with technological and knowledge-based support from the beginning of the design stage or creation of a point cloud right up to the generation of the machine code and the actual building of the part in the machine.

As Additive Manufacturing software applications continue to mature, it will become possible to display Additive Manufacturing parameters in the relevant product data management and business planning software.

4.2 Applications and Markets

This section considers the anticipated future development of Additive Manufacturing applications and markets. It begins by discussing the key drivers of these developments, before moving on to present an overview of the general characteristics required for Additive Manufacturing to be commercially viable. Finally, it describes the advances that are expected to come about in current areas of application and the new application areas that are likely to emerge.

Drivers

The main driver of future growth in Additive Manufacturing will continue to be the **flexibility** that it offers in terms of part **design**. Chapter 3.2 provides several examples of how the technologies can produce finished parts in shapes that were previously almost impossible to realise. Moreover, Additive Manufacturing can help to speed up existing processes. For instance, it allows a company’s sales department to rapidly build a physical model to show to potential customers. There is also a lot of public interest in Additive Manufacturing. This is demonstrated by the growing number of conferences on applied Additive Manufacturing (e.g. *inside3Dprinting*) and the numerous publications on the subject. One of the reasons for this strong public interest is the fact that some technologies can be used **at home**. Additive Manufacturing benefits like no other technology field from the availability of home 3D printers. The innovative shapes of parts produced by hobbyists are attracting a lot of attention in online communities and are also fostering interest from industry. In order to support the continued growth of Additive Manufacturing, it will be crucial to discover further valid industrial applications and communicate them effectively to the public (see also the second statement from the group led by Leopoldina).

Mass Customisation will be another driver of future growth in Additive Manufacturing. This term refers to the production of individually customised items at mass production prices [Pil06], for example customised running shoe soles. The American sporting goods company *New Balance* uses its customers' biomechanical data to produce soles tailored to their individual running style [WC13]. Customised solutions like this allow companies to differentiate themselves from the competition and avoid the "commodity trap" where companies compete almost entirely on the basis of price. Additive Manufacturing is a key technology for this type of customised goods and services [CMM+14]. It is particularly profitable compared to conventional manufacturing technologies when used for low production volumes. Since it does not require any tools, almost no setup time is necessary. It allows manufacturers to incorporate customers' individual requirements into the product design and makes it easier for them to produce small series. However, customised finished products are at present still the exception. This is due to the high cost of the post-processing operations currently required to achieve a high-quality surface finish, for example.

Decentralised Production will be another key driver. The speed with which digital data can be shared means that it is theoretically possible to produce goods on demand anywhere in the world. In Additive Manufacturing more than in any other field, all of the relevant know-how will in future exist in digital form, from the design stage (3D CAD data) to the materials, process parameters and post-processing operations. In practice, however, this vision is subject to a number of limitations (see Chapter 3.5). For instance, the necessary machinery, materials and personnel still need to be available at the decentralised locations. The aviation industry is an ideal candidate for decentralised production. It is characterised by worldwide demand for spare parts, long product life-cycles, high warehousing costs and the need to minimise the time that planes spend on the ground. Aircraft spare parts must be kept in stock all over the world so that parts can be rapidly replaced whenever the need arises. In the future, individual spare parts could be produced and fitted locally on demand as long as the technologies and parts are able to meet the relevant certification requirements. This would reduce warehousing and transport costs and cut maintenance times. The underdeveloped transport infrastructure in many Third World countries is another factor that favours this solution. In these locations, it may even be profitable to make simple objects by Additive Manufacturing. This could also result in the creation of new value structures. 3D4D (3D for Development) could make it possible to produce urgently needed basic consumer goods (e.g. lab equipment) close to the place where they will be used [Hom16].

All of these different factors are also strong drivers of the development of Additive Manufacturing's underlying joining techniques. Parts that are relevant to safety must meet particularly high standards in terms of the powder state, chemical composition and purity of the materials used.

Characteristics Required for Additive Manufacturing to be Commercially Viable

- Low production volumes (currently approx. <1000 units a year)
- Small part dimensions
- Use of expensive materials or materials that are difficult to process using conventional methods

- Instances where parts or components are currently too heavy
- High costs resulting from (scheduled and unscheduled) downtime of complex manufacturing systems
- Conventional design that requires a lot of chip removal by conventional machining resulting in a large percentage of the initial material ending up as scrap
- Very long product development times due e.g. to the time needed to make the necessary tools
- Products with high operating costs compared to their purchase price (e.g. aircraft)
- Decentralised demand for spare parts
- Instances where only limited designs are possible using conventional manufacturing technologies (e.g. heat exchangers) – geometries that cannot be produced any other way
- Individually customised products (e.g. hearing aids)
- Products with laborious conventional manufacturing processes involving multiple stages (e.g. hearing aids)
- Products requiring multi-stage assembly of individual components made from the same material (see *General Electric* fuel nozzle – Chapter 3.2)

Developments in Current Areas of Application

Additive Manufacturing will continue to grow in its established areas of application, provided that the technologies' critical success factors are fulfilled (see Chapter 3.5). However, the prediction that it will outcompete and replace other technologies will for the most part not come to pass, since the performance profiles of the different technologies are too different. Additive Manufacturing will continue to gain ground in the **aviation industry** where it will primarily be used for "secondary structures" (i.e. parts that are attached to the load-bearing portions of the fuselage) [Woh16]. In the future, the principal benefits of Additive Manufacturing for the aviation industry will still relate to lightweight design and the reduction of the "buy-to-fly ratio", i.e. the weight ratio of the material used to make a part and the weight of the finished part in use. This calculation should also take into account the total energy used to manufacture powders as opposed to solid materials. It may eventually be possible to integrate conductive tracks and simple electronic components into parts during the build process. Parts for the **space industry** will in future be built directly in space, allowing better use to be made of the limited room onboard launch vehicles [Del14a].

In the **automotive industry**, although Additive Manufacturing is at present rarely used to make final parts, it has already been employed for many years to produce prototypes and assembly aids. The technology's low productivity and high investment costs are currently barriers to its use for the mass production of automotive parts. In the future, it may be possible to make certain add-on components additively, for instance dashboards and embedded electronic components [Del14b]. If machine manufacturers gradually succeed in delivering the lower machine and material prices and faster build speeds demanded by the automotive industry, then large-scale Additive Manufacturing could become a reality in this sector by 2035, initially for premium models but eventually also for volume models.

The use of Additive Manufacturing will also continue to grow in the field of **medical and dental technology**, particularly for making prosthetics, orthotics, dental crowns, implants and medical devices [EOS13], [Woh16].

Emergence of New Application Areas

In addition to these established areas of application, the experts anticipate that in the future Additive Manufacturing will also penetrate new fields (the group led by

Leopoldina will take an in-depth look at these fields the second statement):

In the not too distant future, Additive Manufacturing machines will be used to build microscopic objects in what is commonly referred to as **nanoprinting** [RAE13]. Even today, Additive Manufacturing makes it possible to scale the full functionality of laboratory equipment down to a credit-card-sized "lab-on-a-chip". This enables rapid diagnosis of medical conditions in remote locations, for example [Hom16]. In the field of medicine, "**bioprinting**" applications including the printing of human tissue and even entire organs are currently under development.

Additive Manufacturing has already been used for several years for rapid model building in the field of **architecture**. It facilitates the holistic appraisal of architectural designs by making it possible to produce complex architectural models of buildings and even entire urban planning models [Sto13]. The first 3D-printed houses are already being built today [Woh16], [RAE13]. One recent example is a 3D-printed office building with a floorspace of 250 m² in Dubai [Nic16].

California has established itself as a global pioneer in additive technology for **civil engineering**. It has been trialling and continuously improving the practical use of Additive Manufacturing to build houses for more than ten years (using a technology known as "contour crafting") [Kho04], [Mol13-ol]. Contour crafting is a variation on Fused Deposition Modelling™ that allows lines of concrete to be laid down with pinpoint accuracy. Researchers are hoping that this technique will make it possible to reduce the time and cost of building houses thanks to material, weight and energy savings

Additive Manufacturing is also becoming increasingly popular in the realm of **art and culture**. More and more artists are using computers to design and model their artistic creations with the assistance of CAD software and CAD scanners [Mon16], [Pan13-ol]. Additive Manufacturing is also frequently used to produce replicas of lost, weather-damaged and intentionally or unintentionally destroyed paintings and artefacts, especially in the field of archaeology.

If the technologies continue to develop as expected, they will also have the potential to deliver significant benefits for specialised low-volume applications with high end-user life-cycle costs (TCO: Total Cost of Ownership). For example, it seems likely that Additive Manufacturing will find applications in **special machinery engineering** (low volumes, low certification costs for parts and manufacturing processes). It is also likely that sectors with a significant catalogue business and traditionally high production volumes, such as the **mechanical joining technology** industry, will use Additive Manufacturing to make low-volume variants (e.g. special connectors) so that they can tap into new market segments [Wor14a]. Potential applications are also being trialled for **cooling and air conditioning systems**. The efficiency of heat exchangers, for example, is largely dependent on their geometry and the materials they are made from. However, conventional manufacturing methods impose constraints on heat exchanger design. Additive Manufacturing could enable significant improvements in heat exchanger efficiency [MW15-ol].

In the **electronics industry**, there will be several niches where the use of Additive Manufacturing will be commercially viable for low-volume applications with high potential for functional integration. One example is the use of SLM™ to make moving coil cartridges for record players. An ingenious shape means that the cartridges can ignore undesirable vibrations without needing to be unduly heavy [Ort16-ol]. Research has also been ongoing for a number of years into the use of Additive Manufacturing to embed conductive tracks in solid parts so that sensors can be situated in inaccessible locations [GWP13], [Woh16]. A lack of conductive and insulating materials that can be processed in the same machine to create a composite part is currently preventing this vision from becoming a reality.

The **petroleum industry** also stands to benefit from Additive Manufacturing. In this industry, even the briefest interruption of extraction processes can be extremely costly. Moreover, spare parts such as pipeline connectors must be kept in stock all over the world so that they can be fitted as quickly as possible whenever the need arises. It is conceivable that in the future the required spare parts could be made directly in the location where they are needed [Woh16].

In most areas of application, Additive Manufacturing will complement conventional technologies – it will only replace them completely in a handful of cases. It is producers who perform manual processes that are most likely to be replaced, rather than the manufacturers of standard, mass-produced goods, who have very mature manufacturing processes [FLT14]. The **hearing aid industry** is a dramatic example of just how fast things can change – the entire industry in the US converted to Additive Manufacturing in around 500 days [Dav15]. Until recently, the production of hearing aid shells was a very laborious, multi-stage process involving several different techniques such as centrifugal casting [Del14c]. Additive Manufacturing has slashed the time required to make these items. First, an impression of the ear is taken; this is then scanned using a laser, converted into a digital model and built by an Additive Manufacturing machine. Only then are the electronics mounted in the hollow space provided.

The above examples demonstrate that actors from many different industries are currently seeking out applications for Additive Manufacturing. It is therefore anticipated that in the future the technology will be used across a very wide range of application areas.

4.3 Potential Developments in Value Networks

As outlined in Chapter 3.3, value networks containing a variety of different roles have formed around the core process of Additive Manufacturing. Figure 4-1 illustrates three key options in which value networks could potentially change in the future. Examples of the options “replacement” and “enhancement” can already be found today.

Replacement: New Actors Occupy Established Roles

As the industrialisation of Additive Manufacturing continues, established machinery and plant engineering players are joining the fray, using expertise from other industries to develop new machines or improve and automate existing ones. 2D printing companies, for example, are now selling Additive Manufacturing machines for business customers. *Hewlett Packard* was just the first of many such companies to enter this market. However, Additive Manufacturing is also attracting actors far removed from the mechanical engineering industry. Some firms that specialise in acting as an interface and control either the logistics or access to the (end) customer are taking advantage of their key position, especially in the consumer goods business. It is quite conceivable that a scenario could occur in which online mail-order companies receive digital orders which they farm out to third-party logistics providers. Using their decentralised manufacturing infrastructure, the logistics providers subsequently make and deliver the product, with social networks providing the platform for sharing

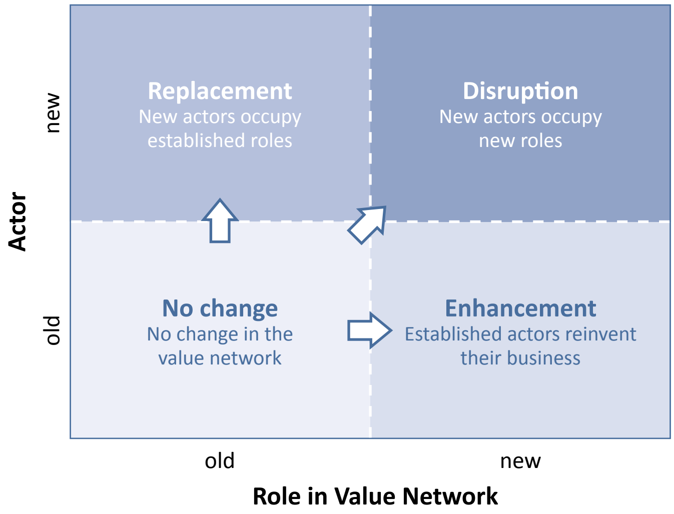


Figure 4-1: Potential developments in value networks (Source: authors' own illustration)

data and models. As indicated in Chapter 4-1, software companies like *Autodesk* are also entering the Additive Manufacturing market. Since the key know-how for Additive Manufacturing technology exists in digital form, software companies could become more important players in this market than for other comparable manufacturing technologies.

Enhancement: Established Actors Reinvent their Business

In tomorrow's competitive environment, today's actors will carry out more stages of the manufacturing process in-house (forward and backward integration). Although there is no universally valid correlation between vertical integration and commercial success, companies' average level of vertical integration can be expected to increase. The reason for this assumption is that specialisation tends to become more prevalent when a technology is approaching full maturity, i.e. when it is harder for companies to differentiate themselves through product innovation [Deu14]. One example of a company that has increased its vertical integration in this way is *materialise*. Initially a manufacturing service provider, it has expanded its business to include software development, an online shop and digital web services. Thus *materialise* is no longer simply a traditional manufacturing service provider – it has become a fully-fledged enabler of its partners' business models. This allows its partners to concentrate on customer relations and product design, safe in the knowledge that they have real-time access to Additive Manufacturing capacity. Furthermore *trinckle 3D* was originally founded as a platform operator and service provider. However, it now supplies cloud-based CAD data customisation software and is thus another example of a company that has increased its vertical integration. *General Electric*'s plans to acquire machine manufacturers *Concept Laser* and *arcam* also fall into the "enhancement" category, since *General Electric* was formerly a customer of both companies [Reu16-ol].

Disruption: New Actors Occupy New Roles

Completely new roles occupied by new actors are also appearing in the Additive Manufacturing value network. However, these new roles may already be established in other industries. One novel idea for this type of role is the notion of a crowdsourcing machine developer who would run idea competitions inviting interested parties to design new machine concepts or enhance existing machines. The completed designs would be built by the customer with specialist support. This would make it possible to build sophisticated machines capable of fulfilling the requirements of the desired application without any constraints. The theoretical basis for this approach is the concept of a "bottom-up economy" [Red11]. One frequently-cited example of a company that has put this idea into practice is US auto manufacturer *Local Motors*, whose aim is to make it possible for members of the public to design their own cars and build them in local "micro-factories" [LM16-ol]. In the Additive Manufacturing value network, this idea is at odds with the prevailing market approach, where industrial Additive Manufacturing machinery and equipment is developed by individual actors or closed development strategic partnerships. Furthermore, it remains to be seen whether the key factors for its success will actually come about, i.e. 1) that different customers really will have very different requirements for the same type of machine and 2) that they will be able to cope with the technological complexity.

Disruptions are difficult to predict. They are driven by novel technologies (technology push) or cross-industry innovations [Ech14]. It seems unlikely that any such disruptions will occur during the next five years. This is because the technology's key performance indicators (productivity, reliability, etc.) will at least initially continue to be developed by actors in established roles (see Figure 3-17). Consequently, "replacement" and "enhancement" will be the dominant development options over the next few years.

4.4 Business Models

It is often claimed that Additive Manufacturing technology will bring about lasting changes in existing business models and even result in the emergence of completely new business models (see Chapter 3.4) [RS14], [RB15], [BHB16], [KPM14]. In actual fact, however, this has not yet come to pass. There are essentially two observations that can be made about the impact of Additive Manufacturing on future business model innovations [FLT14]:

Tried-and-tested Business Models from other Industries will continue to be adapted

Until now, competitors in the Additive Manufacturing market have largely differentiated themselves on the basis of product innovations, i.e. improvements in machinery and equipment performance. This is possible because it is still a relatively immature technology. At present, there is a rather tentative attitude towards business model innovation, with a tendency to draw on tried-and-tested models from other industries. *Stratasys*, for example, has adopted a business model based on the "razor and blades" principle, with a significant percentage of its turnover coming from the sale of expensive filament. Another example of an adapted business model is the development of a system business around the core Additive Manufacturing machine business. For instance, as well as materials and machines, manufacturers *3D Systems* also provide design software, a printing service and an online shop for CAD models. A number of complementary business models may also be observed. These are business models that, although not sustainable in their own right, serve to strengthen another business model. One example of this type of model is the online platform *thingiverse* operated by machine manufacturers *Stratasys*. The platform provides freely downloadable CAD models in order to encourage people to buy the company's consumer machines [FLT14], [JKP16].

Additive Manufacturing as a Catalyst of Business Model Innovations

Even though there are no signs of it at the moment, it is nonetheless perfectly possible that at some point in the future Additive Manufacturing could result in the emergence of completely new business models that would subsequently be adapted by other industries. This is because in principle almost no setup time is necessary for Additive Manufacturing. As a result, mass customisation is now feasible in markets where it would previously have been impossible using conventional methods. Shorter product life-cycles are also possible, since the cost of changing from one product variant to the next is no longer as high. In addition, users of the technology could in theory serve multiple markets and try out different business models in each one. This would allow rapid trial-and-error testing of Additive Manufacturing business models, with the successful ones being transferred across to other markets [RS14], [PS13].

This approach, known as "cross-industry business model innovation", is illustrated by the following simple example. A company that makes gear wheels and mountings decides to try and grow its business by supplying products to small special machinery manufacturers. To do so, it employs two different business models. It involves customers in the development of its customised mountings, for example via an online platform. The gear wheels, on the other hand, are produced using a traditional build-to-order approach.

4.5 Projected Market Growth and Funding Initiatives

As outlined above, in the future we can expect a significant improvement in the performance of Additive Manufacturing technologies, together with the emergence of new markets and application areas. This section will describe the projected growth of the Additive Manufacturing market and provide an overview of the funding initiatives that exist to promote the technologies' establishment.

Projected Market Size

Since the year 2000, the Additive Manufacturing market has experienced average year-on-year growth of 15.6 percent, rising to as much as 35.2 percent between 2013 and 2014. In 2015, total global sales of products and services related to Additive Manufacturing amounted to 4.5 billion euros. This figure includes machines, materials and services in the industrial and consumer markets [Woh16]. Some machine manufacturers saw an increase in new orders for machines of up to 65 percent in the 2015 financial year [SLM16-ol].

These growth figures stimulate projections of the future size of the Additive Manufacturing market. According to a study carried out by strategy consultants *Roland Berger*, the global Additive Manufacturing market will be worth around 6 billion euros in 2020 [RB15]. The consulting firm *Wohlers Associates*, on the other hand, puts the figure at 19.1 billion euros [Woh15]. Evidently, the forecasts are still subject to considerable uncertainty – as recently as 2011, *Wohlers Associates* was predicting a global market size of just 4.6 billion euros for 2020 [Woh11]. McKinsey Global Institute research suggests that Additive Manufacturing could have an overall economic impact of up to 480 billion euros a year by 2025 [CSS14-ol].

Although there are substantial differences in the Additive Manufacturing market size projections published in the literature, one thing that they all agree on is that the global market for this technology field will continue to grow strongly in the future.

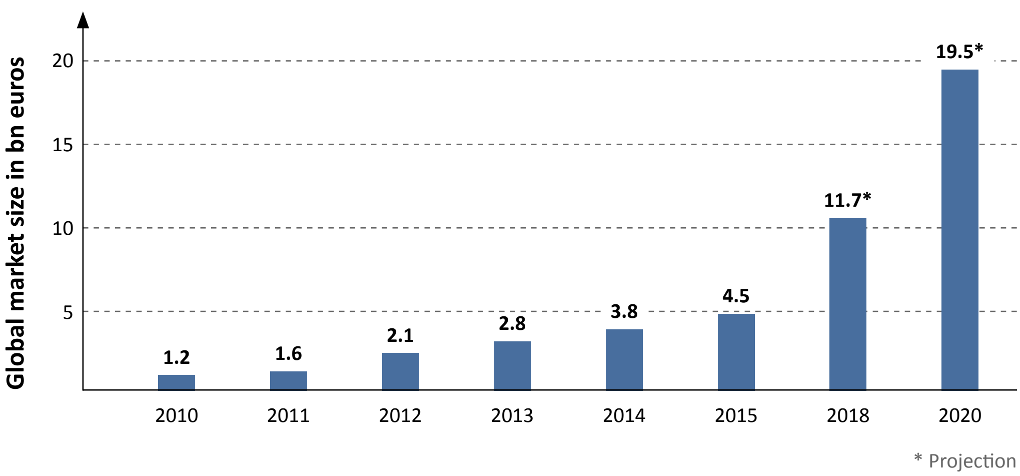


Figure 4-2: Size of global Additive Manufacturing market (Source: [Woh16])

Funding Initiatives in Germany and other Countries

Several countries around the world view Additive Manufacturing as an important area of innovation that can contribute to their prosperity and are therefore providing substantial funding support to their domestic industries [Ens14], [EFI15]. In particular, certain countries that in recent decades have focused on the service sector as the future of their economies now regard Additive Manufacturing as a key pillar of their reindustrialisation strategies [Ens14].

Germany

In Germany, there have been several calls for proposals relating to Additive Manufacturing over the past few years, both in the field of materials science and engineering and in the area of production research. The call for proposals "Additive Manufacturing – Individualised Products, Complex Mass Products, Innovative Materials (ProMat_3D)" supports R&D projects in both fields. In addition, as part of its regional funding programme "Zwanzig20 – Partnership for Innovation", the Federal Ministry of Education and Research (BMBF) is supporting partnerships between research institutions and industry in eastern Germany through the project "Additive Manufacturing – The 3D revolution for product manufacturing in the digital age (Agent3D)" [Bmb13-ol], [Bmb15-ol]. The Collaborative Research Center 814 – Additive Manufacturing was established in 2011. Its second funding phase began in 2015, with funding from the German Research Foundation (DFG) to the tune of approximately 10 million euros [SFB16-ol]. Additive Manufacturing also features in certain DFG Priority Programme sub-projects (e.g. SPP 1542: Concrete light).

The BMBF framework programmes "From Material to Innovation" and "Innovation for Tomorrow's Production, Services and Work" are providing funding for transnational research projects involving partnerships between research groups from academia and industry in Europe through the "Materials for Additive Manufacturing" priority theme of the "M-era. Net II Call 2016". Approximately 40 million euros are available through the call across the whole of Europe.

EU

According to the European Commission, Additive Manufacturing is a driver of the digital transformation in Europe and offers the opportunity to strengthen Europe's manufacturing industry [EFI15]. In 2012, the European Commission's "Industrial Policy Communication" highlighted Additive Manufacturing as one of the most important elements of the "Industrial Landscape Vision 2025" [EK12-ol]. Under FP7, the EU provided 160 million euros of funding for more than 60 projects. Additive Manufacturing is also one of the Key Enabling Technologies (KETs) in the "Horizon 2020" EU Framework Programme for Research and Innovation [Tor14].

US

In the US, funding is provided not only for industrial Additive Manufacturing applications but also for the "maker movement". The National Network of Manufacturing Innovation (NNMI), which was established in 2012, includes *America Makes*, a public-private partnership funded to the tune of approximately 50 million dollars. In February 2014, a second national research laboratory called the "Digital Lab for Manufacturing" was launched with initial government funding of $70 million [Ens14]. This figure will rise to a total of $320 million through additional funding from industry, higher education institutions and government. Additive Manufacturing is one of its priority themes [MH14-ol]. An insight into the US funding landscape is provided in a report by the Institute for Defense Analyses that describes the role of the National Science

Foundation (NSF) in the development of Additive Manufacturing in the United States [IDA13-ol]. Funding is also being provided for projects on the contour crafting of building structures at the Southern University of California [Kho04], with one long-term goal being to use the manufacturing technology being developed there for space travel.

China

China is concerned that reindustrialisation in the US and Europe could make it less attractive as a manufacturing location [EFI15]. Consequently, the government is trying to strengthen the country's domestic industry by investing a total of 245 million US dollars over three years in institutes belonging to the state-funded *Asian Manufacturing Association* and in several Chinese universities [Ens14].

5 Theses

This chapter presents and elucidates 21 theses about Additive Manufacturing. The theses are largely based on our analysis of the status quo and the anticipated developments. As such, they succinctly encapsulate the findings of Chapters 3 and 4. The theses provide the basis for the recommendations outlined in Chapter 6. The first section presents the theses regarding the overall industrial conditions (Chapter 5.1). This is followed by the theses about the technology (Chapter 5.2), value networks (Chapter 5.3) and societal aspects (Chapter 5.4).

5.1 Boundary Conditions

Thesis 1: Additive Manufacturing and Industrie 4.0 mutually reinforce each other.

Industrie 4.0 refers to the ad-hoc networking of smart machines, production resources, products/workpieces and warehousing and transport systems via the Internet in order to create efficient value networks. These smart, digitally connected systems enable almost entirely self-organised production. The aim is to make it possible to produce customised products in low volumes down to a batch size of 1 at mass production prices and with extremely short lead times.

Additive Manufacturing and Industrie 4.0 share a number of common features such as high levels of customisation and connectedness and high energy and resource efficiency. The integration of Additive Manufacturing techniques supports some of Industrie 4.0's key characteristics such as ad-hoc value network configuration, mass customisation and logistics and material flow innovations. Consequently, the combination of Additive Manufacturing and Industrie 4.0 will strongly promote overall customisation and flexibility in industrial production.

Thesis 2: Additive Manufacturing techniques are currently very know-how intensive; the key challenge involves successfully combining three types of data:

- **digital 3D models**
- **material formulae**
- **process parameters**

The most important input variables in Additive Manufacturing are the 3D models, material formulae and process parameters. The 3D models describe the shape of the part being built, while material formulae and process parameters such as laser intensity and scan speed affect the part's properties. Achieving the desired part properties and reproducibility requires the correct combination of these three input variables which all affect each other reciprocally; extensive practical know-how is needed to find this combination. One of the keys to successful deployment of Additive Manufacturing is to establish knowledge management as a learning process and to embed the cycle of externalisation, combination, internalisation and socialisation in the company's culture [NT97].

Thesis 3: Parts can be made close to the place where they are used; the only thing that needs to be sent to the manufacturing location is the data.

German manufacturers can gain a strategic competitive advantage if they are able to use Additive Manufacturing technology to facilitate flexible and efficient production. Provided that the necessary machines and materials are available, parts could be manufactured as required in the location where they are to be used rather than having to be stored. This would allow e.g. warehousing costs, replenishment lead times and delivery distances to be reduced. The necessary data would typically be stored centrally in clouds or on company servers and would be sent or streamed to wherever it was needed.

Thesis 4: Additive Manufacturing will only become widely adopted if parts consistently and reproducibly meet defined quality standards.

Additive technology is still relatively young and its results are still strongly influenced by individual users' practical know-how and experience. Additive Manufacturing will only become widely adopted if quality standards are defined and can be met consistently and reproducibly. This will require an in-depth understanding of the factors affecting manufacturing systems, based on mathematical models or behaviour-based AI models.

Thesis 5: The focus of product piracy will increasingly switch to the data.

Making a copy of a physical product is a laborious process and the results are often inferior. Data, on the other hand, may be copied at will without any loss of quality. If product pirates possess all three of the key data sets, then as long as they know how to use the manufacturing technology it will be much easier for them to produce high-quality copies. Product pirates and competitors are thus increasingly switching their focus to these three data sets. Although in principle this problem could also be an issue with other methods of production, in practice it is particularly relevant to Additive Manufacturing, since the process chain know-how may exist in digital form in the three key data sets.

Thesis 6: The new level of design freedom calls for design guidelines.

While Additive Manufacturing offers a far greater degree of design freedom than conventional manufacturing processes, different Additive Manufacturing techniques all have their specific limitations. Design guidelines can help design engineers to design products that make the most of Additive Manufacturing's advantages whilst avoiding any drawbacks. A first attempt at addressing this issue has already been made in VDI standards 3404 and 3405, which provide a useful overview of what Additive Manufacturing is currently capable of. However, many current design guidelines are limited in scope and cannot be directly applied to individual part designs [Ada15].

Thesis 7: A half-hearted attitude towards innovation and unfair international competition threaten Germany's position as a leading Additive Manufacturing supplier.

Additive Manufacturing technology is an area where small and medium-sized German machine manufacturers have a particularly strong global leadership position. In fact, they are currently struggling to meet the high demand from industry. In view of this situation, they do not appear to regard further improvements to Additive Manufacturing techniques and closer, coordinated alignment of material and process advances as a priority. Some market players are content merely to make incremental improvements to existing systems. The established machine manufacturers are protected against new competitors by key technology patents – cross-licensing of patents is often the only way for new actors to enter the market. Nevertheless, new competitors are now emerging in other parts of the world, among other things thanks to strong government backing. These competitors have close ties with research institutes in their own countries and sometimes ignore the established actors' key patents. If German machine manufacturers and material developers fail to keep up with the growing demand whilst at the same time significantly improving Additive Manufacturing techniques and achieving closer integration of material development, purity improvements and processes, then there is a danger that global competitors could overtake them in the long run.

5.2 Technology

Thesis 8: Additive Manufacturing offers a new level of design flexibility.

In principle, building objects layer by layer eliminates some of the design constraints of conventional techniques such as the need to provide access for subtractive tools or to ensure that the part can be removed from its mould. This means that complex geometries and hollow structures that would involve joining several individual parts together if conventional techniques were used can now be built in a single step. However, it is impossible to avoid a staircase effect similar to the jagged edges found in 2D printing. Depending on the Additive Manufacturing technology, there can also be other constraints. Overhangs, for example, often require the use of support structures in order to counteract the effect either of gravity or of residual stresses caused by temperature gradients. These support structures must be accessible so that they can be removed once the build is complete. Design to Additive Manufacturing is thus only a realistic proposition for certain techniques and requires the entire process chain to be taken into account. Only a few basic guidelines on process-oriented design engineering have so far been published.

Thesis 9: Additive Manufacturing process chains are different to those of other manufacturing techniques.

Data plays a particularly important role in Additive Manufacturing process chains. Unlike plastic injection moulding, for example, Additive Manufacturing does not use physical forming tools that embody both the part's shape and the relevant process know-how. Standards and instruments on a par with the solutions for other manufacturing technologies do not currently exist for the special aspects of the digitalised steps in the Additive Manufacturing process. In the main, this applies to the data privacy of all the stakeholders, fail-safe operation, protection against tampering by third parties, traceability, data consistency and interoperability between different manufacturers' machines.

Thesis 10: Additive Manufacturing is already established in specialised fields, but shortcomings compared to competing technologies are an obstacle to its more widespread adoption.

Although Additive Manufacturing is already established in certain niche applications, there is still considerable potential for it to be more widely adopted. Depending on the application, Additive Manufacturing must compete with conventional manufacturing technologies in terms of cost, quality and speed. One important factor where traditional manufacturing has the upper hand is the ability to produce large numbers of items efficiently. Consistent quality is another key deliverable that is particularly critical for high-volume production. It will be important to leverage Additive Manufacturing's potential here too, for instance through closed-loop control systems for the Additive Manufacturing process and through a completely open process chain, from the CAD system to the numerical control code for Additive Manufacturing machines.

Thesis 11: Specific part properties can be achieved by varying material formulae and process parameters.

All Additive Manufacturing techniques are characterised by a specific interaction between material and process parameters. This interaction is largely determined by the system technology, whether or not the material has been developed to meet the technique's specific requirements, and the purity of the feedstock and freedom from contamination of the process environment. The resulting part properties determine the potential areas of application and how competitive the additive technology is compared to conventional manufacturing. For many additive technologies, there is relatively little published information about the key interactions compared to the practical know-how that actually exists within the relevant companies. Moreover, the fact that monopolies are beginning to form in certain cases does nothing to promote knowledge dissemination. In addition, Additive Manufacturing is still unable to simultaneously make multi-material parts from key structural and functional materials. One promising vision is to make objects with gradient properties where rather than simply having a binary choice of whether or not to use a particular material for each spatial element, it is possible to specify gradients of practically any desired material properties (e.g. electrical, optical, mechanical or chemical).

5.3 Value Networks

Thesis 12: Additive Manufacturing will bring about major changes in value networks. It remains to be seen how it will transform aspects such as goods and services, supply and demand, the goals and power of the different actors and the appearance of new competitors.

Additive Manufacturing technologies are constantly developing, providing companies and collaboration networks with new business opportunities. In the future, the business processes of procurement, production, distribution and waste disposal will be more closely connected to each other. The strong interdependencies between the different business areas will change the structure of Additive Manufacturing value networks, allowing inventory levels and lead times to be reduced. Spare parts logistics providers could potentially also develop new business models such as "AM as a service", intensifying the competition for a slice of the profits. The new industrial end users are not yet fully aware of the opportunities arising from this trend. Moreover, the dramatic changes resulting from the Additive Manufacturing of parts and products will lead to the emergence of new competitors. The appearance of new products and the ability to profitably make customised parts down to a batch size of 1 will make reliable production planning very difficult.

Thesis 13: Additive Manufacturing will revolutionise the spare parts business in certain areas, especially spare parts logistics.

One advantage of Additive Manufacturing is that items can be made in any location. This has certain benefits for the production of spare parts. Today, spare parts often have to be transported over long distances and are in some cases no longer even available for older models. Additive Manufacturing allows spare parts to be made near to the customer or even by the customer themselves in the case of individual parts that are not too big. This makes it possible to reduce downtime and the associated costs. Parts can be built with an Additive Manufacturing system anywhere in the world – it is simply a question of digitally transferring the 3D CAD models and material formula and machine parameter data sets to the relevant location.

Thesis 14: Process chain digitalisation promotes new business models.

Additive Manufacturing process chains can be compared to the mechanisms and processes of other predominantly digital industries such as the digital music and film industries. The establishment of new online platforms for industrial and private use will place high demands on all aspects of data and information processing. These online platforms make it possible to create a marketplace for 3D CAD models, material formulae and process parameters which can be obtained either via a one-off download or via a streaming subscription in much the same way as digital music or films. However, a number of data security, copyright and standardisation issues still need to be resolved. The digital music industry, for example, addressed these issues and established standards when the MP3 format was introduced and used for handling digital music products. In order to ensure that Additive Manufacturing also addresses the relevant challenges, machine manufacturers, developers and users will need to work together closely to ensure consistent, standardised information logistics for the three key data sets. This will create a competence network with expertise on security, data interfaces, flexibility and interoperability right across the value chain.

Thesis 15: Part suppliers that are not closely involved in the parts' development are easily interchangeable.

The basis for Additive Manufacturing is provided by digital 3D CAD models, material formulae and the Additive Manufacturing equipment together with the relevant parameter values. The digitalisation of this data set, which is far more automated in Additive Manufacturing than in conventional manufacturing methods, means that manufacturing service providers have fewer opportunities to differentiate themselves from the competition, making them increasingly interchangeable. This threat can be counteracted if they actively engage in the production-oriented development and design engineering of parts specifically for Additive Manufacturing, since this is a know-how intensive process involving production-related knowledge and it is here that the data set is actually created.

Thesis 16: In conjunction with Industrie 4.0, Additive Manufacturing has high commercial potential for innovative products and services.

Before Additive Manufacturing can be rolled out and establish itself in the market, users must first have confidence in the technology. Machine manufacturers and suppliers can provide new services that help to build this confidence. For instance, an additive machine manufacturer could initially help a company that makes structural components by additively manufacturing the parts for them itself. Doing so would show the structural components company the new opportunities and methods that Additive Manufacturing could bring to its own production. This approach significantly reduces the entry barriers for this new manufacturing technology and builds the confidence to conclude deals for innovative services based on new business models. By combining Industrie 4.0 solutions and Additive Manufacturing it would, for example, be possible to create a product-service system where smart manufacturing machines are used to provide a preventive maintenance service. This would result in improved machine availability and high customer loyalty.

5.4 Societal Aspects

Thesis 17: The economic, environmental and societal impacts of Additive Manufacturing are not yet being assessed in a holistic manner.

Additive Manufacturing promises to be more efficient than conventional technologies in terms of costs and material and energy consumption. Because Additive Manufacturing offers greater product design freedom and makes it easier to build lightweight structures, it can deliver material savings of up to 60 percent compared to subtractive manufacturing technologies. Furthermore, in use, these lighter parts reduce the overall mass that needs to be moved, meaning that vehicles require less power, for example. Additive Manufacturing also provides opportunities to improve working conditions. In order to leverage the potential benefits of Additive Manufacturing, companies need instruments to help them assess its positive and negative impacts in a holistic manner.

Thesis 18: Concerted, strategically-driven research will maintain Germany's global leadership.

The past few years have seen a surge in Additive Manufacturing research around the world. In Germany, Additive Manufacturing is addressed by numerous research programmes, calls for proposals, priority projects, committees and consortia. The existing expertise in the relevant disciplines should be pooled and gaps in the research landscape identified. Accordingly, a strategy should be formulated that sets out how Germany can maintain and extend its global leadership by pooling its R&D resources.

Thesis 19: Additive Manufacturing calls for concerted action in school, vocational and higher education training and professional development.

Personnel recruitment for new technology fields is inherently difficult, since the relevant occupational profiles are only just beginning to emerge and the new technologies are not fully established within educational institutions. The entire Additive Manufacturing value network suffers from a shortage of skilled labour that is preventing the technologies from becoming more widely adopted. Visions such as "everyone is a designer" can support efforts to find a solution to this problem. Moreover, it is more important than ever to anticipate the product life-cycle during the product planning and development stage in order to identify the demands and constraints that will affect its future competitiveness. Digitalisation and the rapid rate at which knowledge is growing in this area pose further challenges for future occupational profiles. Consequently, a master plan should be developed and implemented by the key stakeholders, encompassing the entire spectrum of school, vocational and higher education training and professional development in the field of Additive Manufacturing.

Thesis 20: Additive Manufacturing is transforming skilled workers' skills profiles.

The skills profiles of industrial manufacturing workers, particularly skilled workers, are expanding to include the ability to use and appraise Additive Manufacturing technology. This trend is being driven by the twin factors of customer focus and a life-cycle approach. New customer focus possibilities are coming about thanks to the digitalisation of industrial value creation and the growing interconnectedness of companies and their customers. A life-cycle approach to the economic, environmental and socio-technical design dimensions opens up new perspectives and potential successes for future industrial value creation.

Thesis 21: Despite its popularity, home use Additive Manufacturing will continue to have a negligible role compared to its industrial counterpart.

Additive Manufacturing is an extremely popular technology because it addresses customer-driven trends such as mass customisation, increasing numbers of variants and demand for individually customised products. At first glance, Additive Manufacturing seems to offer people new and fascinating opportunities to participate in manufacturing processes themselves. However, home producers' euphoria tends to be dampened by the hard reality of having to comply with guarantee, product liability and certification requirements, for example. Consequently, for the time being it can be assumed that home production will continue to be negligible compared to its industrial counterpart.

6 Recommendations

A number of recommendations can be made with a view to driving the development of Additive Manufacturing technologies, opening up new areas of application and optimising the industrial applications. These recommendations are aimed at focusing research funding so as to overcome the remaining practical obstacles associated with the various manufacturing technologies, establishing norms and standards in order to simplify development processes and promoting cooperation between the different actors.

In addition to government research funding agencies, the recommendations are thus primarily aimed at the leading companies where Additive Manufacturing is expected to play an increasingly important role in the future. As well as contributing through their own research into the development of materials and manufacturing techniques, the main challenge for these companies will be to rapidly establish the infrastructure needed to integrate the new additive methods with their existing production processes as efficiently as possible. For its part, government can create a favourable environment for the technologies' future development by introducing measures to support young start-ups and by making the relevant changes to school education and training curricula. In general, closer cooperation between research and industry in this field would also be desirable. Standardisation organisations such as DIN/ISO could contribute to this process.

Research

In order to improve the productivity of Additive Manufacturing and reduce its drawbacks compared to conventional manufacturing technologies, research should be conducted into production processes, materials and part properties, with the results being fed back into the systems engineering process.

The machine hour rate of industrial Additive Manufacturing systems is very high compared to conventional production technologies. Furthermore, the strength and quality of additively manufactured parts only rarely compare to conventionally manufactured parts. Material behaviour is also variable and has not yet been the subject of in-depth research. These are the main obstacles to the commercially viable use of the technologies for producing high volumes and high-quality parts in industrial applications. On the other hand, the various additive technologies still have a lot of untapped potential. Particularly in the automotive and aviation industries, users of the technology already have plans for high-volume production.

In order to make full use of the new design flexibility opportunities, systematic research should be carried out with a view to producing concrete design guidelines covering all the different Additive Manufacturing technologies.

Although Additive Manufacturing provides a high level of design freedom, there are still certain constraints such as the requirement for support structures in some cases and the need to post-process the parts. Design to Additive Manufacturing is only feasible for certain additive technologies and must take the entire process chain into account. There are currently very few basic ground rules and no specific process-oriented design engineering guidelines. These will therefore need to be formulated and incorporated into the relevant training and professional development provision together with the underlying practical know-how.

Develop new data formats for Additive Manufacturing as soon as possible.

The current standard .STL file format suffers from a number of problems, since important information is lost during the conversion of 3D CAD data and inconsistencies can occur. This means that extensive post-processing of the data set is often necessary. Moreover, there are numerous proprietary data formats for transporting information that cannot be saved in .STL. A concerted R&D effort will be required before data formats can be standardised. Any new data formats will need to guarantee the interoperability of equipment made by different manufacturers and ensure user access to the relevant information. They will also need to work with existing IT systems (PDM, ERP). It will only be possible to achieve widespread acceptance in the industry and among the maker community once these requirements have been met. The first steps are already being taken in this direction with new, open data formats such as .3MF.

Analyse the ways in which Additive Manufacturing could potentially change and impact on value networks, the economy and society as a whole.

This analysis should include upstream and downstream manufacturing processes, product use and recycling. It should evaluate the benefits in terms of social, economic and environmental sustainability arising from the new value creation structures associated with decentralised, demand-based production. One example is the reduction of the high warehousing and logistics costs involved in supplying spare parts.

Implementation

Standardise the three data sets of digital 3D models, material formulae and process parameters.

In the long run, the productivity and part quality improvements demanded by industrial users will require a standard, universally accepted data format that can be used for 3D models, material formulae and process parameters. It will also be necessary to develop appropriate quality criteria (e.g. indicator systems) for Additive Manufacturing. This will be critical e.g. to enabling classification of data, materials, processes and parts. Since there are also currently still some gaps in our technical and physical understanding of Additive Manufacturing processes, there is a significant research requirement concerning the generation of the three data sets. If the goal of a widespread standard data format for the three data sets is achieved, it will become much easier for product pirates to produce high-quality copies. It will therefore be essential to identify the potential threats to each of the three data sets and implement integrated protection strategies for them.

Additive Manufacturing requires dedicated quality assurance methods and processes.

It will be necessary to develop methods and processes for measuring, testing and verifying the quality of additively manufactured parts. This will require the relevant process parameters to be identified, monitored and adjusted during the manufacturing process using a process model.

Accelerate the implementation of basic research in industrial applications.

One possible approach involves strengthening pre-competitive research collaboration between the federal government and industry. The establishment of regional demonstration centres and technology clusters can also play a major role in translating research into practice. Successful pilot implementations and the use of the technology in specific industries can serve to demonstrate the opportunities and risks, as well as the range of applications that already exists today. Another concrete approach would involve the implementation of large-scale collaborative projects in the form of public-private partnerships. Last but not least, it is necessary to explore whether there is any potential in Germany's relatively weak AM start-up scene for driving improvements to Additive Manufacturing techniques.

Strategies are needed for integrating Additive Manufacturing with widespread conventional manufacturing systems.

The integration of Additive Manufacturing techniques with existing production processes will require the development of standard routines, process-based quality management and new machine systems capable of robust manufacturing. One key requirement will be to ensure that the automation of Additive Manufacturing systems is brought up to the level expected of conventional production systems both today and in the future. The transformation of industrial value creation that we are beginning to witness in the context of Industrie 4.0 will undoubtedly play a significant role in this regard.

Creation of decision-making tools capable of meeting future strategic planning challenges in connection with Additive Manufacturing.

If visions such as decentralised production and the prosumer paradigm come true, then value networks will be transformed from the ground up. In order to be prepared for this change, it will be necessary to develop scenarios for the relevant actors in these new value networks. It will also be important to create instruments for assessing the economic, environmental and societal impacts of Additive Manufacturing. Scenarios and impact assessment instruments are urgently needed decision-making tools for the strategic positioning of the actors in the industrial value network.

Stimulate and support a dynamic start-up scene in order to leverage Additive Manufacturing's high potential for innovation.

Germany possesses extensive know-how in the fields of production research and industrial automation and is thus well placed to make improvements to existing machinery and equipment. However, this evolutionary approach is unlikely to create completely new Additive Manufacturing technologies and business models – the potential to do this lies instead with established actors from other industries and with start-ups. In particular, public funding agencies should introduce measures to stimulate start-ups and make funding available to them in order to leverage the potential for innovation and promote a new and vibrant start-up scene.

Education

Augment traditional occupational profiles for skilled workers with new skills for Additive Manufacturing technology.

In the future, Additive Manufacturing will become a standard manufacturing technology in many industries. It must therefore be fully incorporated into vocational training and professional development provision. Before this can happen, teaching staff at vocational institutions will first need to receive the appropriate training. The rate at which the technologies are developing constitutes a particular challenge. It will therefore be necessary to establish digital teaching and learning platforms and make use of new knowledge transfer methods such as Massive Open Online Courses (MOOCs). In view of the high innovation rate in the field of Additive Manufacturing, it will also be necessary to determine whether professional development certificates should only be valid for a limited period of time.

Make use of Additive Manufacturing's potential for teaching STEM subjects in schools.

Additive Manufacturing technologies have huge potential as a teaching aid in schools. They can be employed to bring the design and manufacturing processes to life. Living labs where students have the opportunity to use 3D CAD systems and home 3D printers themselves can help to make technology more tangible and get young people excited about STEM subjects.

Funding

Establish a research programme geared towards implementation of the dual strategy of securing Germany's position as a leading Additive Manufacturing supplier and market.

German machine and equipment manufacturers and material developers are already global leaders in the supply of Additive Manufacturing systems and materials. At the same time, many German companies are trying to use Additive Manufacturing technologies to gain a competitive advantage. In the future, it will be important both to secure Germany's position as a leading Additive Manufacturing supplier and to create favourable conditions for Additive Manufacturing to increase German companies' competitiveness. This statement has outlined the challenges that will be encountered along the way. Overcoming these challenges will require an extensive and concerted research programme that should address the following topics:

1) Process chain automation
2) Basic materials and process science research
3) New alloys and thermomechanical treatments specifically designed for Additive Manufacturing techniques
4) Productivity improvements
5) Standard feedstocks with high purity and appropriate morphology
6) Quality control
7) Reproducibility of part properties
8) Selective modification and variation of part properties (gradient properties)
9) Multi-material processing
10) Data integrity (data privacy, data security and data consistency)
11) Safety and security in cyber-physical production systems
12) Product piracy prevention
13) Impacts of decentralised production on value networks and holistic impact assessment

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List of Abbreviations

3D CAD	Three-Dimensional Computer-Aided Design
3DP	3D printing™
ABS	Acrylonitrile-Butadiene-Styrene
AI	Artificial Intelligence
AM	Additive Manufacturing
CAD	Computer-Aided Design
DLP™	Digital Light Processing™
DMD™	Direct Metal Deposition™
DMLS™	Direct Metal Laser Sintering™
EBAM™	Electron Beam Additive Manufacturing
EBM™	Electron Beam Melting™
ERP	Enterprise Resource Planning
FDM™	Fused Deposition Modelling™
FLM	Fused Layer Manufacturing
ICT	Information and Communication Technology
LBM	Laser Beam Melting
LENS™	Laser Engineered Net Shaping™
LLM	Layer Laminated Manufacturing
LMD	Laser Metal Deposition
LOM™	Laminated Object Modelling™
PC	Polycarbonate
PDM	Product Data Management
PI	Polyimide
PLA	Polylactic acid
PMMA	Poly(methyl methacrylate)
SLA™, STL	Stereolithography
SLM™	Selective Laser Melting™
SLS™	Selective Laser Sintering™
STL	Standard Triangulation Language, Stereolithography or Surface Tessellation Language

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