B

Additive manufacturing ("3D printing")

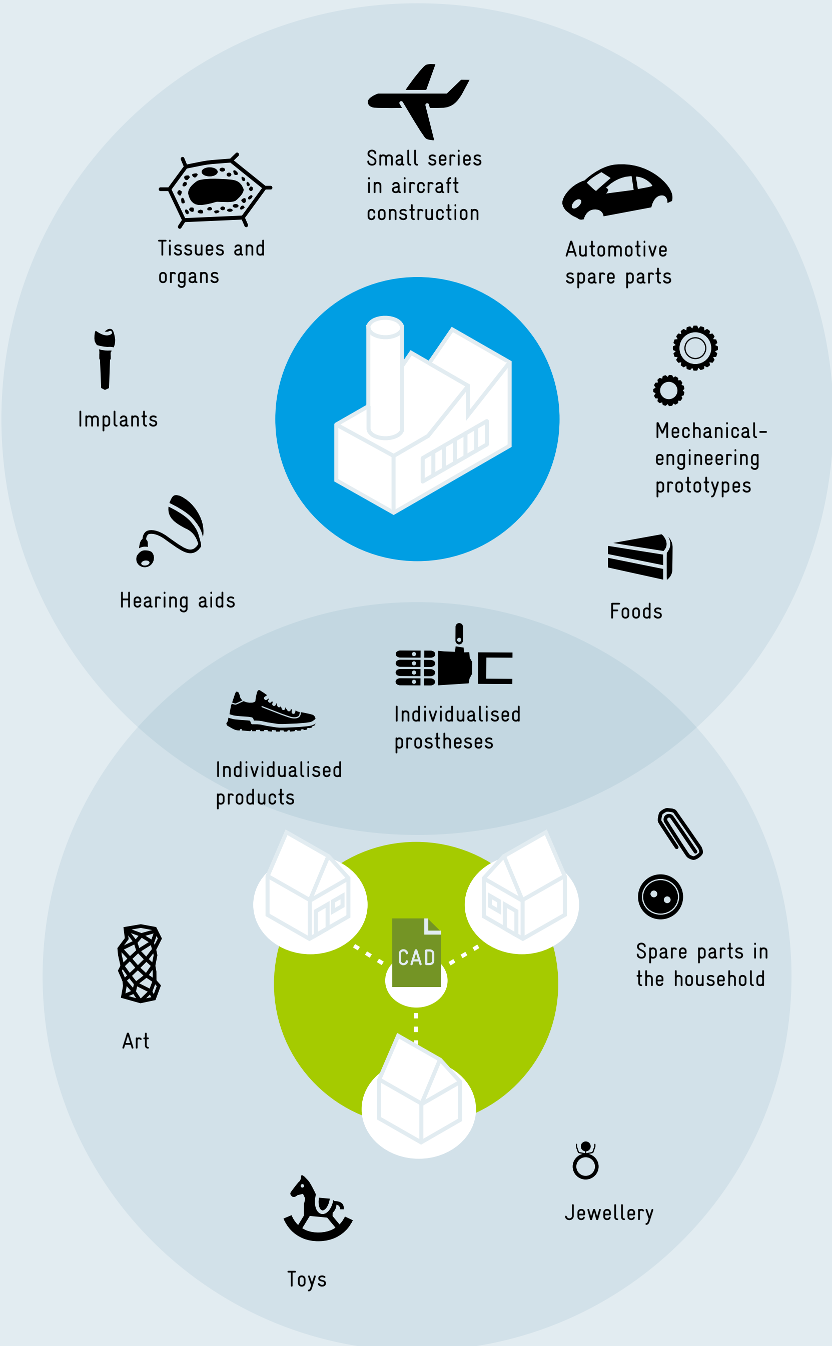
Additive manufacturing (AM) or 3D-printing allows the direct manufacture of three-dimensional physical objects on the basis of digital information, e.g. in the form of a 3D-CAD data set. In this manufacturing process, products are usually manufactured by applying layer after layer of metals or plastics.

Applications in industry

A wide variety of materials are used in industry, e.g. metals, plastics, ceramics, even living cells.

Private applications

AM technologies are also used by private individuals. In the "maker movement", users network, exchange digital designs and individualise products.

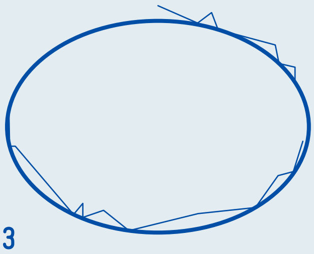


Source: Own depiction.

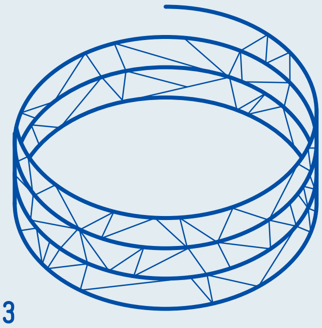
Data
Download

Global turnover from the sale of AM goods and services in US dollars

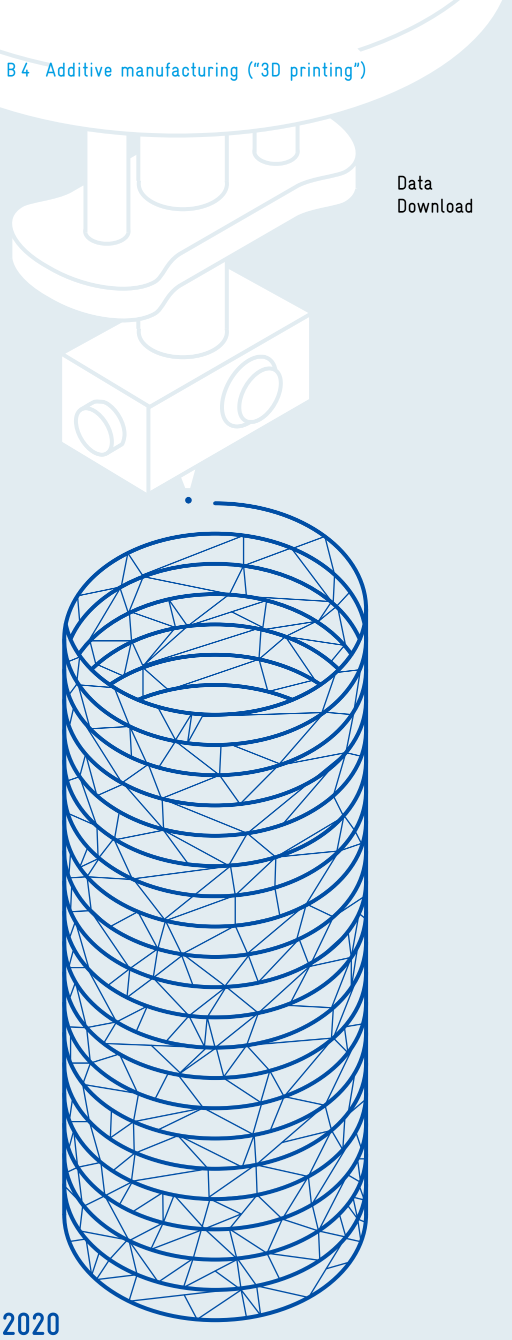
AM goods include 3D printers, material, accessories and software, as well as AM-related services used to make additively manufactured products. Additively manufactured products are not included here.



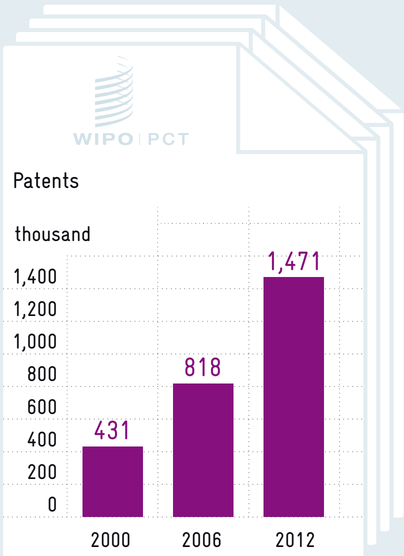
2003
529 million US dollars

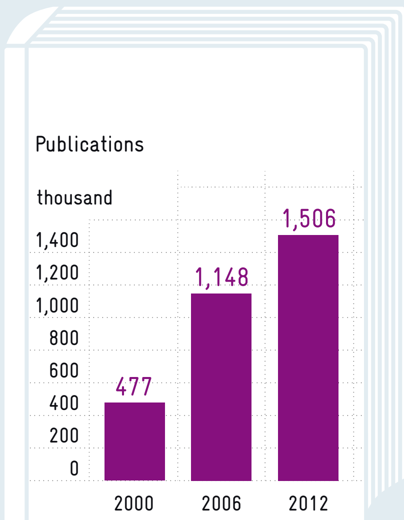


2013
3.07 billion US dollars



2020
21 billion US dollars





Patents and publications

AM is a research- and innovation-intensive field. The number of scientific publications and patent applications worldwide in this field has risen strongly in recent years.

Source: Own depiction. Data on turnover: cf. Wohlers (2014: 110ff.), patent and scientific publication data based on written information from Fraunhofer IGD and Prognos AG.

B

B 4 Additive manufacturing ("3D printing")

B 4–1 Status quo and prospects

Additive manufacturing (AM) – also known under the terms "3D printing" or "generative manufacturing processes" – makes it possible to produce three-dimensional physical objects directly from digital information, e.g. in the form of a 3D CAD dataset.[244] 70 Unlike traditional subtractive manufacturing processes like milling and turning, or formative processes like casting and forging, in the case of additive manufacturing processes products are usually made by adding layer after layer of metals or plastics.[245] This principle of layering allows the flexible production of almost any geometry or internal structure, however complex. In this way, it offers almost unlimited creative and design freedom when working with materials.[246] One key advantage of AM is its versatility. AM can be used in a wide range of manufacturing industries – from aerospace to healthcare. It is even possible to build structures with living cells ("bioprinting") with AM.

Furthermore, AM is also becoming more and more attractive for new user groups – both in the industrial sector and in private households – due to falling prices for the technical infrastructure. AM is therefore a suitable way to accelerate – and improve the quality of – product development thanks to the rapid availability of complex prototypes. The streamlining of the production steps enables companies to respond more quickly than traditional manufacturing processes to market requirements at much lower process costs. This can considerably shorten product development and the time to market,[247] enabling companies to react flexibly to shorter product life cycles.[248]

AM is not a completely new technology. However, since the first fully functional system was unveiled in 1984, AM has been used almost exclusively for specific industrial applications such as the accelerated development of prototypes (rapid prototyping).[249] Only since its application possibilities have become ever broader and costs have fallen has AM developed into a technology that is no longer used only in the industrial context, but also by private users, thus attracting a growing amount of public attention.

The technological maturity of AM technologies varies depending on the area of application – industrial automation, medical technology, bioprinting or home-based production by consumers (maker movement. cf. Box 12). Bioprinting and home-based production by consumers are at an early technological stage, whereas industrial AM is already regarded as an established technology.[250]

The Commission of Experts analyses the potential of AM for production and innovation and offers recommendations on whether and how framework conditions should be improved and existing support activities adapted.

Market situation in the field of additive manufacturing

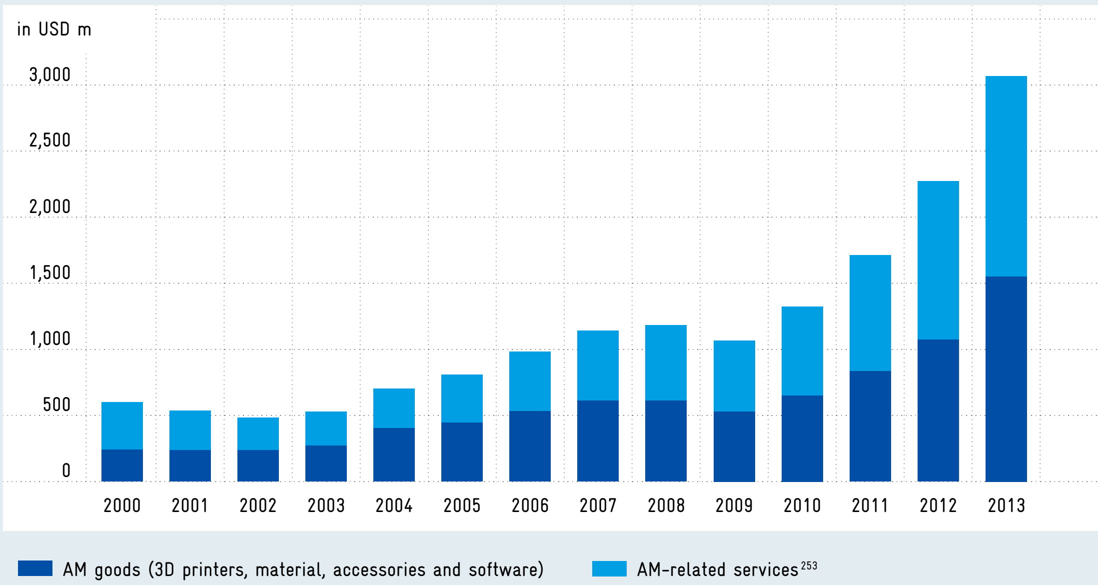
Due to its versatile applications, AM is a much-debated technology that is thought to have a disruptive potential.[251] Products made by additive manufacturing are to be found primarily in the following sectors: motor vehicles and vehicle engines, chemical products, aircraft and spacecraft, machinery for generating and using mechanical energy, medical equipment and orthopaedic products, as well as measuring, monitoring, navigation and other instruments and devices.[252]

There are no reliable estimates on turnover generated by additively manufactured products. Market estimates and forecasts on market development only exist on the supplier side (suppliers of AM goods and AM-related services for producing additively manufactured products). The figures differ considerably depending on how the market is defined.

Fig 04

Data Download

Global turnover with AM goods (hardware and software) and services in millions of US dollars



Source: Cf. Wohlers (2014: 110).

According to a study by a market-research company, global turnover from the sale of AM goods and AM-related services rose from 600 million to 3 billion US dollars per year between 2000 and 2013 (cf. Figure 4).[254] By 2020, annual turnover is expected to rise to about 21 billion US dollars.[255]

Looking at Germany, a study conducted on behalf of the Federal Ministry for Economic Affairs and Energy (BMWi) has concluded that German companies generated between 15 and 20 percent of global turnover in AM goods and services in 2010 (1.3 billion US dollars).[256] Using a narrow market definition, this corresponds to a volume of 200 to 250 million US dollars. If a broader definition[257] of AM goods is used, approximately 1,000 companies making AM-relevant hard- and software or offering such services are operating in Germany. Their turnover for 2010 is estimated at EUR 8.7 billion. Assuming annual turnover growth of up to 15 percent (as the study does), the sales volume of German companies could grow to EUR 35.1 billion by 2020.[258] These rough estimates underline AM's market potential. Prerequisites for such strong growth, however, include constant innovations and the development of new applications.[259]

Supply side: mainly medium-sized companies

The supply side in AM goods and services reflects the typical size structure of Germany's corporate landscape. Almost half of the approximately 1,000 companies mentioned in the above study have fewer than 25 employees. Almost two thirds of the firms generate an annual turnover of less than EUR 5 million. The EU defines small and medium-sized enterprises (SMEs) as firms with up to 250 employees. According to this definition, over 90 percent of the AM companies in the study are SMEs.[260]

The authors of the study classify many of the companies as world-market-oriented technology producers in a good competitive position and with a high propensity to innovate:[261] overall, Germany is a net exporter of AM goods and services.[262] About 160 of the identified companies operate as developers and producers of AM hardware; approximately 240 companies develop AM-relevant software; the remaining companies are either exclusively service providers or offer services in combination with hard- and software solutions.[263]

However, the AM device manufacturers (3D printer manufacturers) with the biggest global market share are located in the USA.[264] The most important German producers, which also are very well positioned on the world market, include EOS Electro Optical Systems GmbH (Krailing, turnover in 2013: EUR 45.8 million), SLM Solutions GmbH (Lübeck, EUR 21 million), Voxeljet AG (Friedberg, EUR 11.7 million), Concept Laser GmbH (Lichtenfels, EUR 7 million), Envisiontec GmbH (Gladbeck, EUR 4.4 million) and Realizer GmbH (Borchen, EUR 2.6 million).[265] In addition, established German mechanical engineering companies like Trumpf AG are also active in the development and manufacture of AM devices (3D printers).[266]

Support for additive manufacturing: an international comparison

In the past few years, many industrialised countries have recognised the growing importance of AM and set up support programmes for domestic AM businesses. Some of these programmes are briefly presented below to make it easier to classify Germany's support policies.

USA: The US government attaches great importance to AM and supports research, industrial applications, start-ups and the so-called maker movement.[267] The aim in promoting AM is to rebuild lost industrial production capacity and create new jobs.[268] In this context, AM funding is an integral part of a programme, launched in 2012, called the National Network of Manufacturing Innovation, which included the establishment of the National Additive Manufacturing Innovation Institute (called "America Makes" since 2013) as a pilot facility.[269] America Makes is a public-private partnership of about 50 companies, 28 universities and research institutions, and 16 other organisations; the US government says it has provided 50 million US dollars in funding for the pilot.

The aim is to accelerate the development and transfer of AM technologies into the manufacturing sector and in this way improve the international competitiveness of the manufacturing industry in the USA.[270] President Obama has announced that further Additive Manufacturing Innovation Institutes are to be set up.[271]

China: There are concerns in China that the country might lose some of its attraction as a manufacturing location for the export market. In particular, people fear that US and European companies could develop AM capacity directly within their respective sales markets and thus withdraw some of their production from China.[272]

This is probably why the Chinese government is supporting the development of a strong domestic AM industry. Since 2013, the Asian Manufacturing Association (AMA), a state-supported trading group, has been building up ten institutions engaged in AM research. Each institute initially received 3.3 million US dollars in funding.[273] AM research capacity has also been expanded at some Chinese universities. Overall, China's government has earmarked around 245 million US dollars to fund AM projects over a period of three years.[274] A strong and internationally successful business community has not developed so far; the Chinese AM industry is still dominated by public institutions.[275]

EU: The European Commission calls AM a driver of digital change and is optimistic about the prospects of strengthening Europe's manufacturing sector with the help of AM.[276] At present, there are no support programmes specifically dedicated to AM at the EU level; rather, support is provided primarily in the context of general programmes and application fields.[277] For example, the eighth Framework Programme for Research and Innovation – "Horizon 2020" – is funding research projects on new AM-relevant materials and processes.[278] Furthermore, the EU is responding to the need to create uniform standards and coordinate standardisation activities in Europe with its initiative "Support Action for Standardisation in Additive Manufacturing" (SASAM).[279]

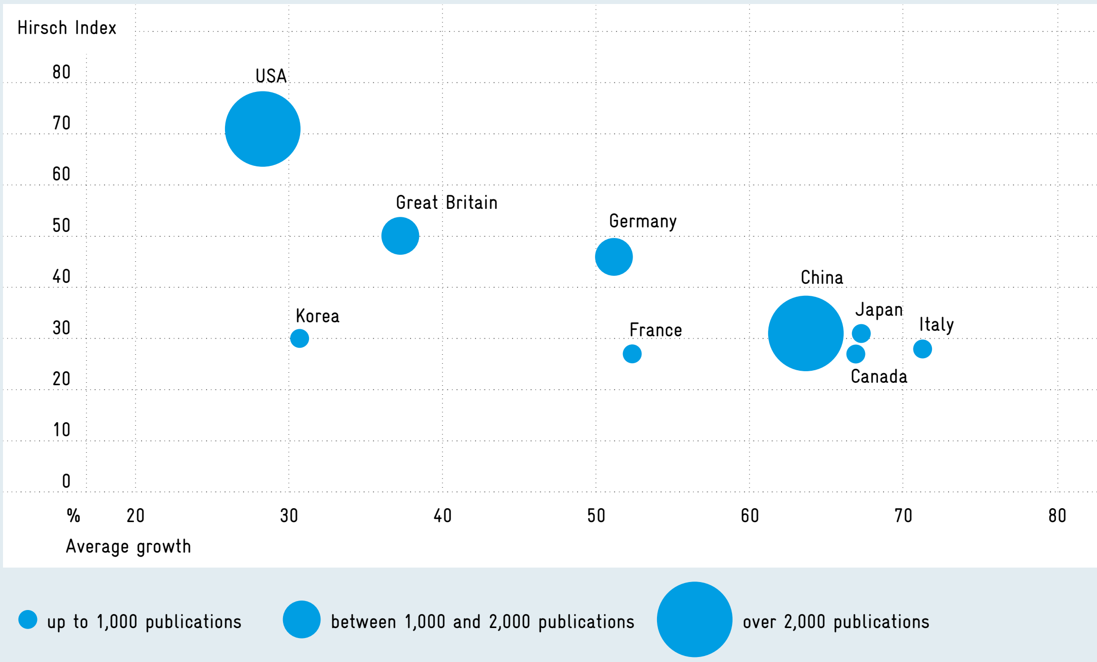
Germany: The Federal Government is promoting AM as part of its institutional funding for relevant non-university research institutions and in the context of federal project funding. The Federal Government has expanded its support activities in the field of AM.[280] As at the EU level, AM is being promoted primarily in the context of specific applications. One example is the BMWi's Gemini Project for the development of viable business models in the context of Industry 4.0.[281] In addition, the BMWi is considering supporting AM in combination with ICT applications.

In addition to this support in the context of specific applications, the BMBF has also initiated measures in the meantime which primarily support AM research by, or cooperation between, research institutes and companies.[282]

Fig 05

Data Download

Number, quality (Hirsch Index) and average growth of AM-relevant publications (2000 to 2014) in selected countries



Source: Scopus. Research and calculations by Fraunhofer IGD.
Note: Calculations of average growth are based on the changes between 3-year time slices over the entire period.

Furthermore, the BMBF promotes AM under the non-thematic Zwanzig20 regional development programme. In this context, the BMBF is providing up to EUR 45 million between 2013 and 2020 for a project called "Additive Generative Manufacturing – The 3D Revolution for Product Manufacturing in the Digital Age".[283] The aim of the Zwanzig20 programme is to promote collaborations between research institutions and companies in the new Länder.[284]

The Commission of Experts welcomes the fact that AM technology is now attracting greater interest in the Federal Government's support programmes. However, an overarching strategic framework for this support seems to be lacking at present.

B 4–2 Publication and patenting activities in the field of additive manufacturing

Increasing publication activities

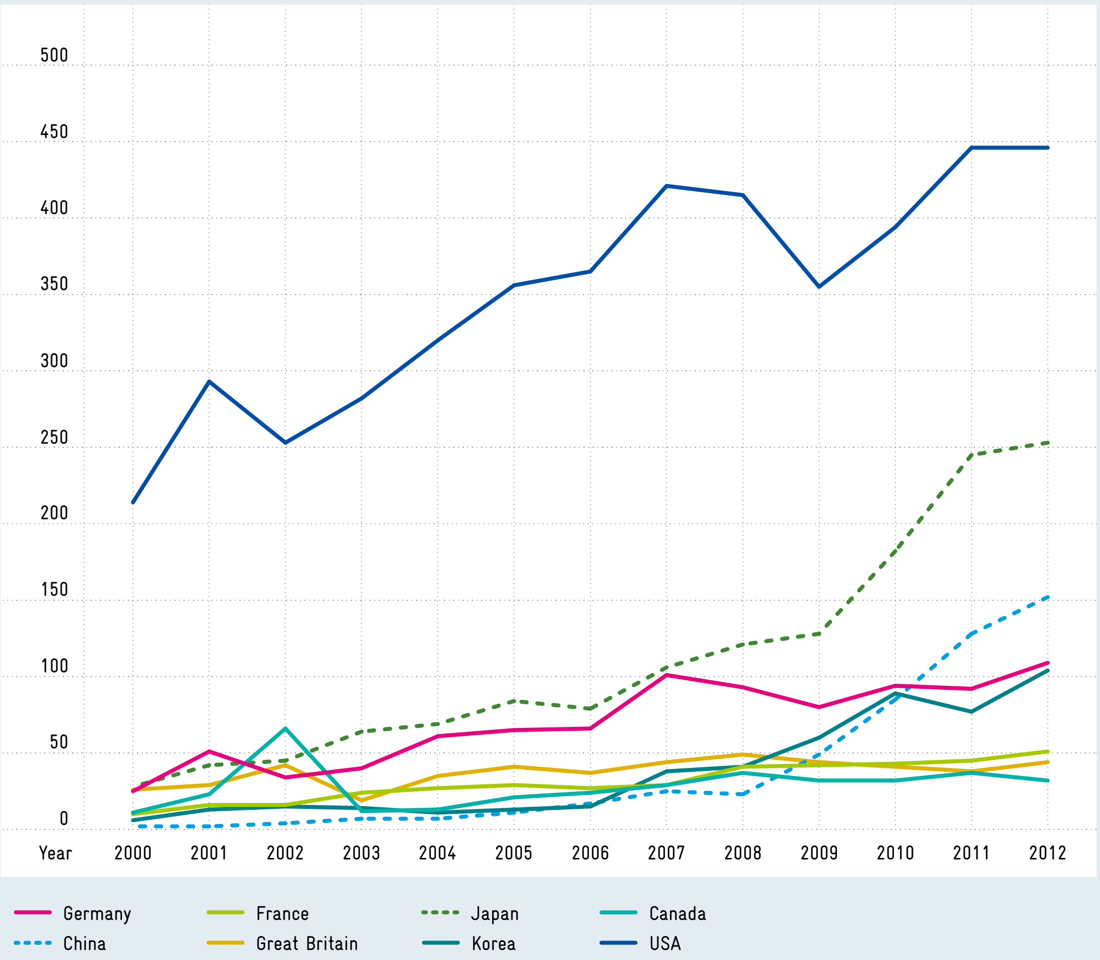
The annual number of scientific publications on AM-relevant subjects[285] almost quadrupled worldwide during the study period – from 477 in 2000 to 1,793 in 2013 (cf. infographic at the beginning of the chapter).[286] Scientists resident in the USA were involved in a particularly large proportion of the publications in this period (cf. Figure 5), followed by China-based and Germany-based scientists. Scientists resident in the UK were in fourth place.[287] The world's most prolific institutions when it comes to publications on AM research are Loughborough University in the UK and Huazhong University of Science and Technology in China. There are three German universities in the Top 30 of the best research facilities worldwide in this field: the Technical University of Munich, the Friedrich Alexander University of Erlangen-Nuremberg, and the RWTH Aachen University of Technology. In addition, publications by scientists resident in Germany are of high quality by international comparison, as measured by the Hirsch Index.[288] Only publications in the USA and the UK are of even higher quality.

The number of scientific publications has grown especially strongly since 2000 in Italy, Canada, Japan and China. In Germany, too, much more is being

Fig 06

Data Download

Development of the number of AM-relevant PCT patent families in selected countries, 2000 to 2012



Source: Database of the European Patent Office (EPO) DocDB/INPADOC. Research and calculations by Prognos AG. Note: Fractional counting[289]

published than in 2000, although the average annual increase is slightly lower than in the countries with particularly high growth rates.

Increase in internationally registered patent families

Worldwide, the number of AM-relevant[290] PCT patent families[291] more than tripled between 2000 and 2012 (cf. infographic at the beginning of the chapter). By far the biggest share of all patent families worldwide in 2012 were applied for in the USA and Japan (cf. Figure 6). Applicants in Germany followed in fourth place. The rapidly growing patenting activities in Asia since 2008 have been particularly striking.

Additive manufacturing's potential for innovation and production

B 4–3

Today, AM already provides an important technological basis for innovative and production processes in industry. This applies in particular to prototyping in product development and to the manufacture of tools for industrial production. Manufacturing based on AM makes it possible to produce in particular small quantities at a lower cost than when traditional methods are used.[292] The time and costs involved in implementing a new design are reduced in this virtually tool-free form of manufacturing ("rapid manufacturing"). For example, it is no longer necessary to adjust casting moulds or other component-dependent manufacturing tools.[293] Instead, only the new, digital design, i.e. a corresponding CAD file, needs to be replaced. And it can be used as often as necessary, also at multiple locations at the same time – without generating high production costs.

The use of AM represents a process innovation that also opens up greater freedoms in the development of new products and allows more product variety. It makes the industrial production of more complex product and part shapes possible.[294] Design activities are less often limited by technical restrictions than in the case of traditional manufacturing processes like casting.[295] The absence of such restrictions means that product design can be geared more towards functionality and customer benefit.

AM allows suppliers to pay more attention to customers' individual needs. For example, perfectly fitting implants or prostheses in medicine require personalised products,[296] and these can be made at lower cost with AM. Today, for example, additive manufacturing methods are already being used almost exclusively to make hearing aids.[297] By contrast, standardised mass products are usually less flexible in their range of applications and offer less individual comfort.[298]

Additive manufacturing: driver of individualised mass production and user innovation

AM enables companies to offer customers simple design tools; in this way consumers can increasingly incorporate their preferences and know-how into the design, innovation and production process. The companies can achieve higher prices in the market, since consumers are usually willing to pay more for self-designed products than for mass-produced products.[299] At the same time, it is less costly for manufacturers to differentiate their products from competitors. In combination with new services and digital production, AM can thus offer technical and organisational ways of establishing an individualised form of mass production.

Up to now, concepts of individualised mass production have been largely based on modularisation approaches. For example, production in the automotive industry is often based on standardised model platforms in which modularisation begins as late as possible in the production process – for cost reasons. AM offers a more flexible process by comparison: in principle, customer preferences can be incorporated quickly at every phase of the value-added chain – also and especially in upstream innovation processes.

In addition to a greater variety of supply thanks to niche products, AM can support the emergence of new business models (cf. chapter A 4), in combination with advancing digitisation and connectedness in the economy and society. Interacting with digitisation and connectedness, AM can lead to a greater decentralisation of production structures in the future and to a further blurring of the borderlines between digital and physical production.[300]

As the prices of AM devices continue to fall, more and more private users are able not only to modify products, but also, for example, to design, produce and distribute the latter over the internet. These users are thus acting in a similar way to decentralised microentrepreneurs. Another term used in this context is the "maker movement" (cf. Box 12) made up of so-called prosumers and user innovators.[301] Accordingly, the maker movement can lead to the participation of new innovators and increase market entry.

Potential of additive manufacturing for reshoring production

Although AM is currently used primarily to produce complex parts, prototypes and small series, the pace of technical change suggests that AM might also be increasingly applied in series production in the future.[302] Labour-intensive manufacturing processes can be increasingly automated by AM. In combination with the possibility of customising products and adapting them quickly to changing customer preferences, the relative importance of labour costs will therefore decline. At the same time, proximity to the customer is becoming increasingly important,[303] making it more attractive for companies to locate their production facilities close to their buyer markets and consumers. In the medium term, AM could thus result in companies reshoring back to Germany production processes they had outsourced abroad. Some countries expect reshoring to develop such a massive impact on their economies, that these prospects are now legitimising comprehensive AM-support measures (cf. B 4-1).

Potential of additive manufacturing for the High-Tech Strategy

The Commission of Experts believes AM could be a key enabling technology. AM can contribute to meeting the priority future challenges defined in the new High-Tech Strategy (HTS; cf. chapter A 3). Industry

Box 12

The maker movement

The maker movement is a group of early adopters and user innovators (cf. chapter B 3) in the AM field. The group is marked by two characteristics. On the one hand, users apply digital tools and software especially frequently to design new products and build prototypes. On the other hand, users in this group are often willing to collaborate and exchange their designs in online communities – in the spirit of an open source culture.

EAt present, it is not possible to say exactly how large the German and international maker movements have become in the meantime, or what long-term growth potential and decentralisation trends they might generate. To date, it is at most a small, but growing number of individual users. However, AM devices for private households and small businesses, so-called desktop 3D printers, are now coming onto the market at a price of around EUR 500, making them affordable for a relatively large number of individual users for the first time.[304] One of the most important producers in this area of AM was MakerBot, which has since been bought by Stratasys for more than 400 million US dollars. Up to 2013, MakerBot had already sold more than 22,000 printers for household use.[305]

On Thingiverse, the world's biggest community platform, more than 130,000 members are now sharing their digital designs. The online trading platform Shapeways has been bringing a large number of designers and end users together since 2007; and with more than 50 AM systems of their own, they even take on the production and shipping of the selected designs.[306] More than 120,000 print products are sold there every month.[307] Their business model, for example, includes offering users tutorials for creating their own designs. At the same time, the first independent start-ups have already emerged that use nothing but Shapeways' production infrastructure.[308] This can be seen as evidence that AM is already successfully promoting the emergence of new business models and innovative services in the internet.

4.0 is one of the central fields of action for the priority future challenge "Digital economy and society". Industry 4.0 means that companies increasingly use cyber-physical systems to network their machines, storage systems and operating resources, creating intelligent factories.[309] The aim of this digital networking is to achieve greater flexibility and decentralise production processes. AM builds on a digital basis and – more than most other technologies – contributes towards making production processes more flexible and decentralised.

AM can therefore be regarded as an important enabling technology for the realisation of Industry 4.0.

AM's broad range of potential applications in the medical field – e.g. the production of personalised medical devices and bioprinting – can make an important contribution to tackling the HTS priority challenge "Healthy Living". On the one hand, AM can help secure the cost-effective provision of healthcare and quality of life for a rapidly ageing population; on the other hand, it opens up new economic prospects for German companies, since Germany is well positioned both in the AM field and in medical technology and medical research.[310]

The use of AM also generates new, important stimuli in education and training. With AM, learners can be familiarised at an early stage with a new, design-oriented way of thinking. The application of AM can teach important innovation-relevant skills and inspire enthusiasm for innovation at an early stage.

In addition, the use of experimental processes can help students to develop a better understanding of mathematics, natural sciences, design and art.[311] However, this means that the education and training of teachers and curricula will have to be adjusted accordingly. At the same time, the necessary infrastructures should be made available in schools and other educational institutions.[312]

Legal framework

AM makes it possible to reproduce and copy products quickly and cost-effectively. In the future, therefore, manufacturers, designers and engineers of products will be confronted with similar problems to those that the music and film industry have already known for years: the illegal reproduction and the commercial and non-commercial distribution of products.[313] AM can also lead to the illegal copying of patent- or design-protected products. There might therefore be collisions with all types of intellectual property rights: e.g. patent and utility model law, copyright law, and trademarks and design law.[314]

In order to make it possible to exploit the innovative potential of AM to increase overall economic welfare, a balance must be found between the legitimate interests of rights owners on the one hand, and the growing possibilities of applicants and innovators on the other.

Clarification is also needed regarding the extent to which manufacturers of additively manufactured products can be held liable for defects. Product liability requires CAD files to be defined and treated as products in the legal sense. However, the legal status of software – and therefore CAD files – has not yet been defined.[315] Yet, even if CAD files were defined as products, product-liability regulations could only be applied in the commercial sphere – which cannot always be clearly distinguished from the non-commercial sector.

It is also unclear to what extent a service provider who creates a product on behalf of a customer based on the latter's CAD file is liable for damage caused by product defects. Furthermore, there is currently no law regulating the production and dissemination of CAD files that can be used to make prohibited goods such as weapons.[316]

B 4–4 Recommendations

AM has the potential to become a key enabling technology. As such, AM can strengthen Germany as an industrial location, limit the shift of value added and employment to other countries, and even reshore value-added chains to Germany. The Commission of Experts therefore recommends reviewing the framework conditions for AM and, where appropriate, to increase funding for research in this field. Research funding should go not only to the technology suppliers, but also to the industrial applicants of AM, in order to jointly expand and develop applications.

Bring actors and disciplines together

- The Federal Government should step up its coordination efforts to bring together experts from different disciplines and applications on cooperation platforms – e.g. in networks and clusters.
- Interdisciplinary research collaboration (e.g. with material sciences and nanotechnology) at higher education institutions and non-university research institutions should be strengthened via appropriate measures, and technology transfer to businesses should be supported further.

Exploit the potential of additive manufacturing for Industry 4.0

- In the context of promoting Industry 4.0, the potential of AM should also be pursued further.
- To reduce information costs and to overcome lock-in effects, the diffusion of AM technologies may require support on the demand side. This may include a stronger focus on AM in best-practice examples for Industry 4.0 and Smart Services to be showcased in the competence centres, which have been announced by the Federal Government as part of the Digital Agenda.[317]
- Current support measures for AM are being provided detached from each other and not in a systematic way. The Commission of Experts suggests that support measures for AM should be embedded in a consistent overall framework.

Clarify standardisation and legal issues – strengthen international cooperation

- The Commission of Experts recommends clarifying unresolved legal issues relating to AM, such as liability, without delay in order to increase legal certainty for innovators. Furthermore, fast technological change in the AM field requires continuous monitoring of the needs for adjustment within the German and European legal framework.
- The Federal Government should set stronger incentives for developing quality standards and for testing and certification activities in the area of AM designs, materials and products.
- European and non-European cooperation in the fields of AM research and standardisation should be promoted to a greater extent.

Integrate additive manufacturing into the education system

– Skills in the use of AM should be taught across the vocational education and training system. AM technologies should be broadly employed not only in the higher-education sector, but also in vocational training and in schools. Parallel to this, teaching staff and vocational trainers should receive relevant training.